Hilbert Transform

and

Stochastic Mechanics

MEET

OPERATIONAL MODAL ANALYSIS (OMA)

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10th International Conference of Experimental Vibration Analysis for Civil Engineering Structures

Politecnico di Milano, Italy - August 30 – September 1, 2023

EVACES 2023

POLITECNICO MILANO 1863

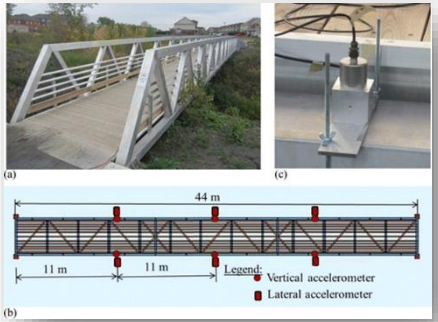
Structural dynamic identification: EMA VS OMA

- Experimental Modal Analysis (**EMA**): Forced vibration (Input/output)

- Operational Modal Analysis (**OMA**): Ambient noise vibration (Only output)

OMA the leading way for Monitoring

- ★ Quick and cheap testing procedures
- ★ Dynamic characterization under operating conditions



Advantages

EMA	OMA
Control of force level	Quick and cheap testing procedures
Identification of nonlinear structural behavior	Dynamic characterization under operating conditions

Disadvantages

EMA	OMA
Temporary interruption of structure functionality	System linearity assumption
Expensive set-up	Superposition of excitation sources

- Zahid, F.B.; Ong, Z.C.; Khoo, S.Y. A review of operational modal analysis techniques for in-service modal identification. *J. Braz. Soc. Mech. Sci. Eng.* 2020, 42:398. Zhang, L.; Brincker, R.; Andersen, P. An overview of operational modal analysis: Major development and issues. In Proceedings of the 1st International Operational Modal Analysis Conference, Copenhagen, Denmark, 26-27 April 2005
- Bendat, J. S., Piersol, A. G.: Engineering Applications of Correlation and Spectral Analysis, John Wiley & Son 1993.
- Ivanocic', S. S., Trifunac, M. D., Todorovska, M. I.: Ambient Vibration Tests of Structures – A Review, ISET Journal Of Earthquake Technology 37(4), pp. 165-197 (2000).

Structural dynamic identification: EMA VS OMA

- Experimental Modal Analysis (**EMA**): Forced vibration (Input/output)

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OMA the leading way for Monitoring

- Quick and cheap testing procedures
- Dynamic characterization under operating conditions

The key hypothesis of OMA are:
the structure can be considered as excited by a white noise process W(t),
System linearity assumption

OMA BACKGROUND

FREQUENCY DOMAIN	TIME DOMAIN	HYBRID METHODS
• Frequency Domain Decomposition (FDD); • Peak Picking + Half Power Bandwith Method (PP+HP); • …	• Stochastic Subspace Identification (SSI); • Auto-Regressive … (ARMA) • …	• Time-Frequency Domain methods

R. Brincker, L. Zhang, P. Andersen, Modal Identification from Ambient Responses using Frequency Domain Decomposition, in Proc. of the International Modal Analysis Conference (IMAC), San Antonio, Texas, February, 2000.

J. Lardies, Modal parameter identification based on ARMAV and state-space approaches, Arch. Appl. Mech. 80 (4), 335–352, 2010.
S. L. Chen, J. J. Liu, H. C. Lai, Wavelet analysis for identification of damping ratios and natural frequencies, J. Sound Vib. 323 (1–2), 130–147, 2009.

Hoa, T.N., Khatir, S., de Roeck, G., Long, N., Thanh, B.T., Abdel Wahab, M., An efficient approach for model updating of a large-scale cable-stayed bridge using ambient vibration measurements combined with a hybrid metaheuristic search algorithm, Smart Structures and Systems, Volume 25, Issue 4, April 2020, Pages 487-499,2020.

Marrongelli, G.,Gentile, C.,Saisi, A Anomaly Detection Based on Automated OMA and Mode Shape Changes: Application on a Historic Arch Bridge, Structural Integrity,11, pp. 447-455, , 2020.

Bilello C., Di Matteo A., Fersini A., Masnata C., Pirrotta A.,Russotto S., A novel identification procedure from ambient vibration data for buildings of the cultural heritage, Atti del XVIII Convegno ANIDIS L’ingegneria sismica in Italia, Ascoli Piceno 15-19 Settembre, 2019.

OMA the leading way for Monitoring

The key hypothesis of OMA is:
the structure can be considered as excited by a white noise process W(t),

MEETS

Stochastic Mechanics

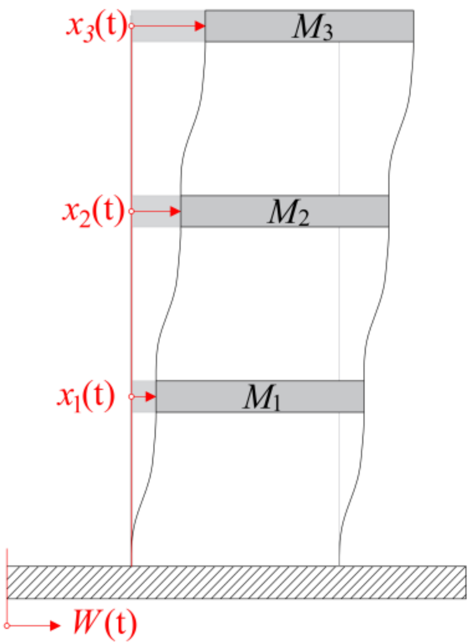
OPERATIONAL MODAL ANALYSIS (OMA)

LINK between research and engineering applications of High Level

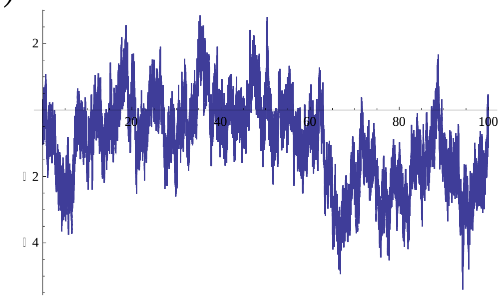
Stochastic Mechanics

MEETS

OPERATIONAL MODAL ANALYSIS (OMA)



$$\begin{cases} \mathbf{M}\ddot{\mathbf{X}}_{(r)}(t)+\mathbf{C}\dot{\mathbf{X}}_{(r)}(t)+\mathbf{K}\mathbf{X}_{(r)}(t)=-\mathbf{M}\mathbf{V}W(t) \\ \mathbf{X}(0)=0; \\ \dot{\mathbf{X}}(0)=0; \end{cases}$$



$$\ddot{\mathbf{X}}(t)=\ddot{\mathbf{X}}_{(r)}(t)+\mathbf{V}W(t)$$

$$\bar{f}_j = f_j\sqrt{1-\zeta_j^2}$$

$\mathbf{M} \rightarrow$ Mass matrix

$\mathbf{K} \rightarrow$ Stiffness matrix

$\mathbf{C} \rightarrow$ Dissipation matrix

$\mathbf{X}_{(r)}(t) \rightarrow$ Response process (Relative displacement)

$\dot{\mathbf{X}}_{(r)}(t) \rightarrow$ Response process (Relative velocity)

$\ddot{\mathbf{X}}_{(r)}(t) \rightarrow$ Response process (Relative acceleration)

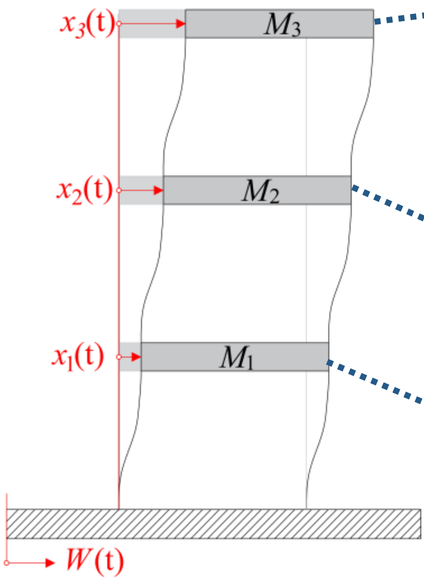
$\mathbf{V} \rightarrow$ Forcing location vector

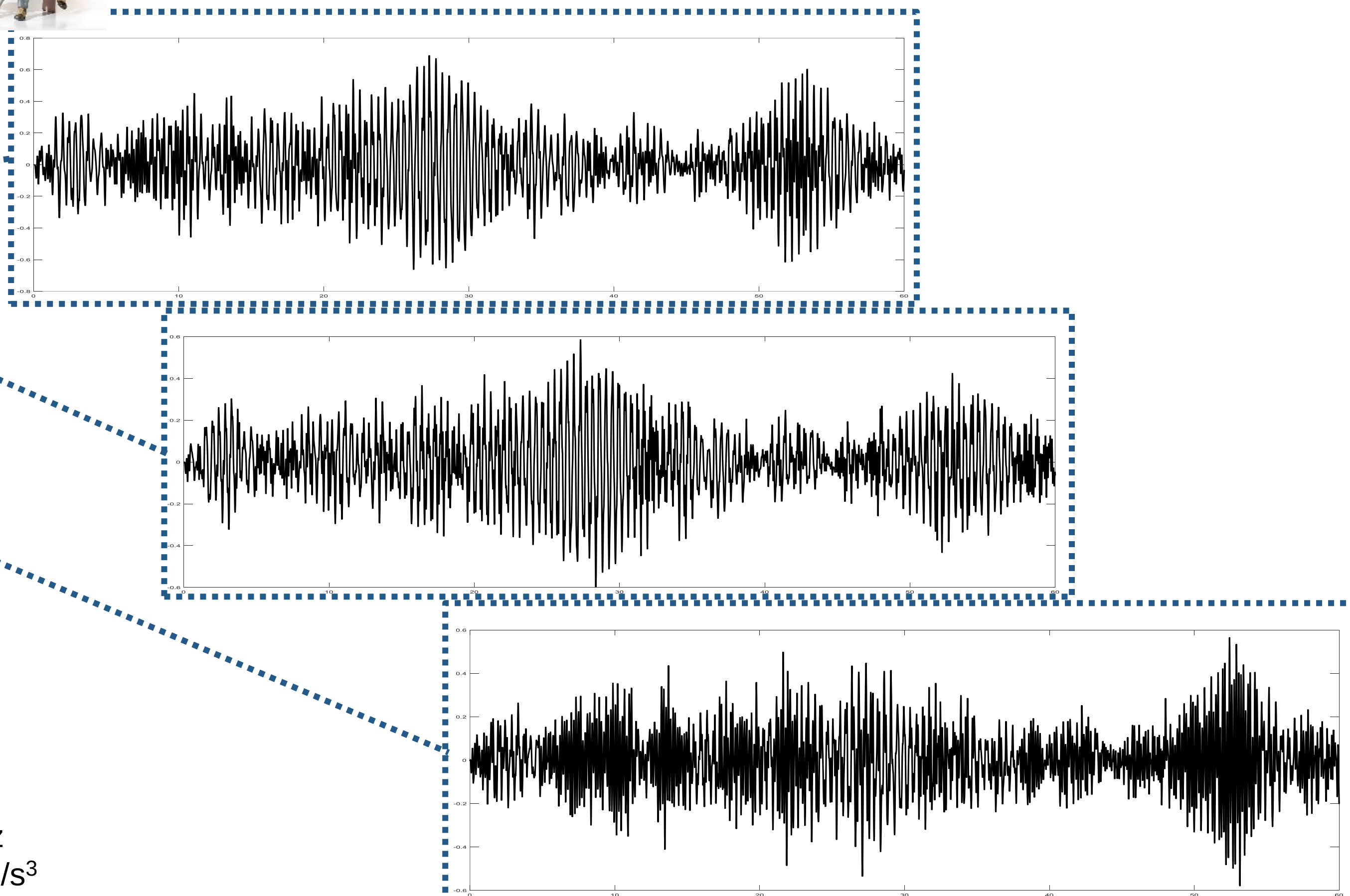
$W(t) \rightarrow$ Ground acceleration process (White noise)

Number of record: 100
Time of recording: 60 s
Sampling frequency: 1000 Hz
S0: $9 \cdot 10^{-5}$ m^2/s^3

Stochastic Mechanics **MEETS** OPERATIONAL MODAL ANALYSIS (OMA)

Structural Output $\ddot{\mathbf{X}}(t)$





Number of record: 100
Time of recording: 60 s
Sampling frequency: 1000 Hz
S0: $9 \cdot 10^{-5}\ m^2/s^3$

Stochastic Mechanics MEETS Operational Modal Analysis (OMA)

Power Spectral Density Function PSD

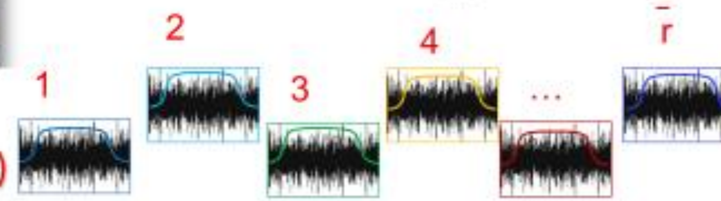
$\ddot{x}(t)$
Acquisition of output signals

Welch's Method

Power Spectral Density (PSD)
$S_{\ddot{x}\ddot{x}}(f)$

- **Step 1:** Acquisition of the output signals

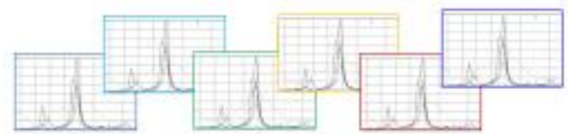
- PSD
- (Welch's Method)

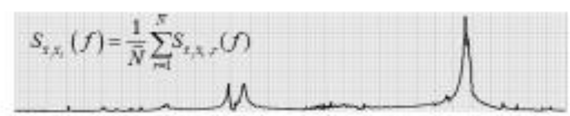


Sub-signals(s)
Overlap(%)
Windowing

PSD estimation

P. D. Welch, *The Use of Fast Fourier Transform for the Estimation of Power Spectra*, IEEE Trans. Audio Electroacoust, 1970





TIME DOMAIN

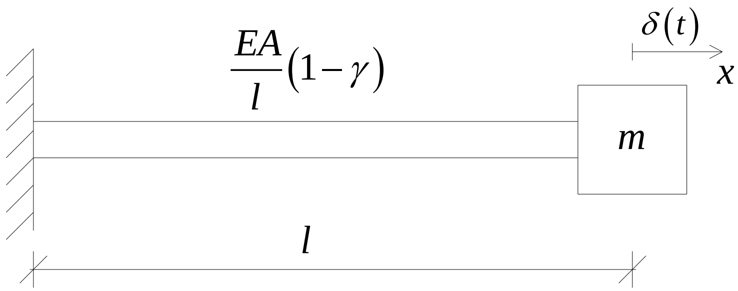
MEETS

Hilbert TRANSFORM

OPERATIONAL MODAL ANALYSIS (OMA)

David Hilbert (1862-1943)

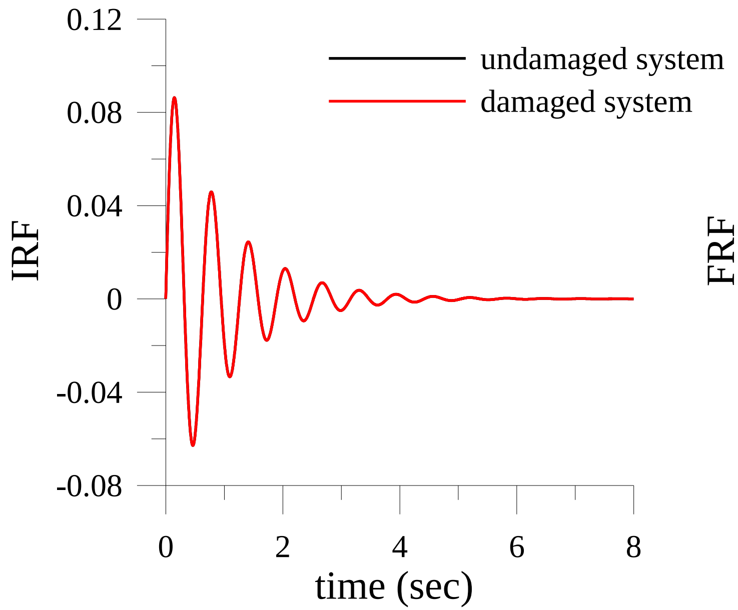
Damage identification SDOF system Statement of the problem

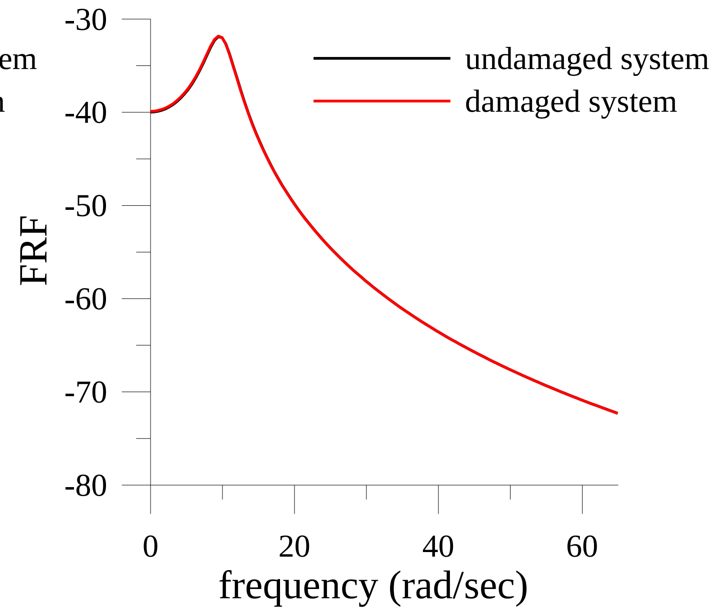


$$\omega_0 = \sqrt{\frac{EA}{ml}} = 10 \text{ rad/sec}$$

$$\Lambda = \zeta_0 \omega_0 = 1 = \text{cost}, \quad \gamma = 0.01$$

$$\ddot{x}(t) + 2\Lambda \dot{x}(t) + (1-\gamma)\omega_0^2 x(t) = \delta(t)$$





Damage Identification SDOF system

Use of Analytical signal

$$y(t) = x(t) + i\hat{x}(t)$$ Analytical Signal

$$\mathrm{HT}\left[x(t)\right] = \hat{x}(t) = \frac{1}{\pi} \wp \int_{-\infty}^{+\infty} \frac{x(\tau)}{t-\tau} d\tau$$ Hilbert transform

$$y(t) = x(t) + i\hat{x}(t) = A(t)\exp[i\theta(t)]$$

$$A(t) = \sqrt{x(t)^2 + \hat{x}(t)^2}$$ Amplitude

$$\theta(t) = \arctan\left[\frac{\hat{x}(t)}{x(t)}\right]$$ Phase

$$\omega_{ist}(t) = \dot{\theta}(t)$$ Instantaneous Frequency

Use of Hilbert Transform and of Analytical Signal

- HT for detecting and quantify system non-linearities.
- Analytical signal for the system characterization.

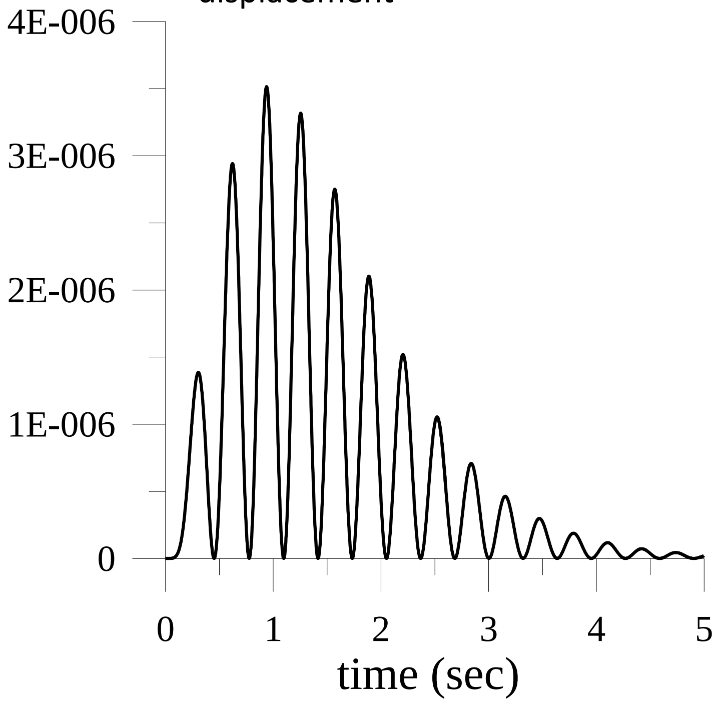
- M. Simon, G.R. Tomlison, (1984) *Journal of Sound and Vibration*, 96.
- G.R. Tomlinson, I. Ahmed, (1987) *Meccanica*, 22.
- M. Feldman, (1997) Journal of Sound and Vibration, 208 .
- S. Braun, M. Feldman, (1997) Mechanical Systems and Signal Processing, 11 .

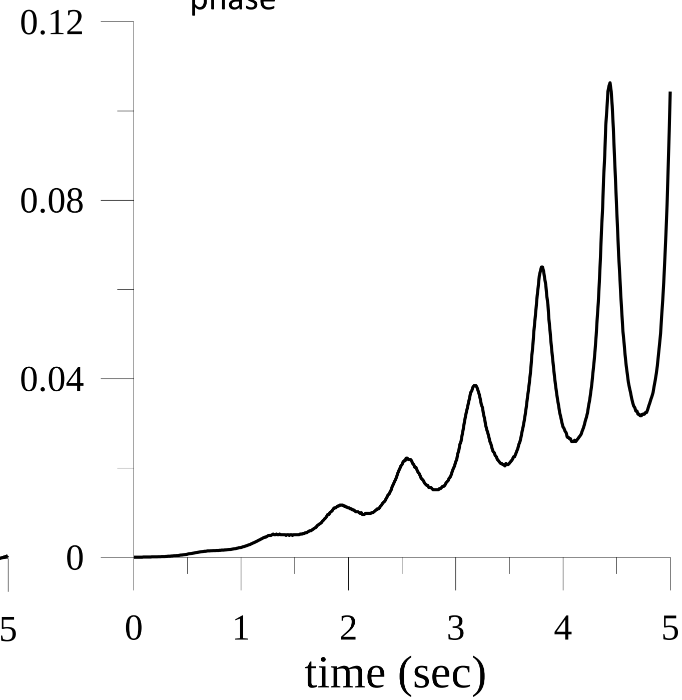
Damage identification SDOF system

$$\left[x^{un}(t) - x^{dm}(t)\right]^2 \qquad \left[\vartheta^{un}(t) - \vartheta^{dm}(t)\right]^2$$

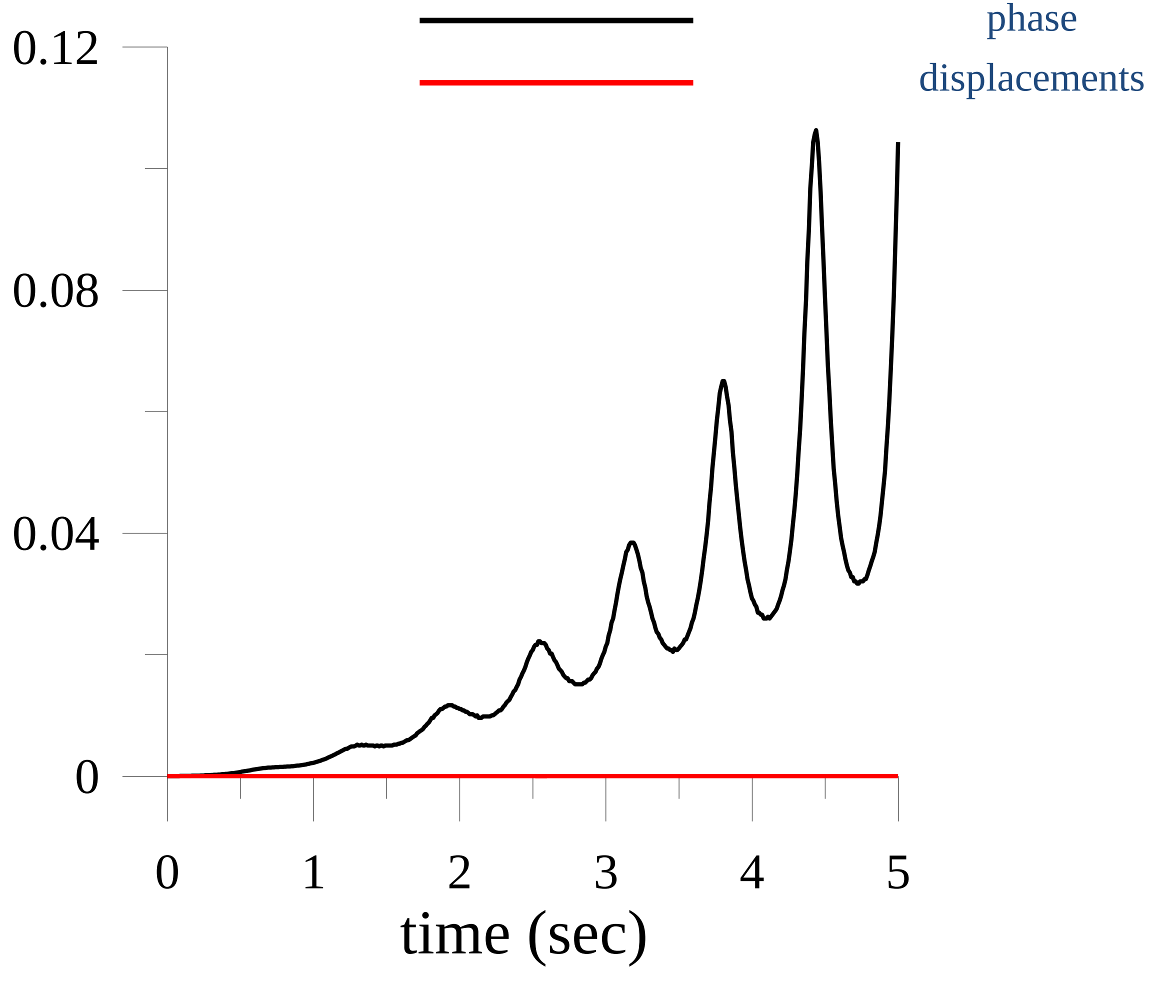
displacement

phase





Damage identification SDOF system



Hilbert Transform

and

Stochastic Mechanics

MEET

OPERATIONAL MODAL ANALYSIS (OMA)

Correlation function

Correlation function

Correlation functions' matrix

$$\mathbf{R}_{\ddot{\mathbf{X}}}(\tau) \qquad R_{\ddot{X}_i \ddot{X}_j}(\tau) = E\left[\ddot{X}_i(t)\,\ddot{X}_j(t+\tau)\right]$$

HYBRID METHODS

PREVIOUS Proposed Method: MDOF Systems

• ϕ modal shapes

• ζ damping ratios

• f frequencies

$\ddot{x}(t)$

Acquisition of output signals

Welch's Method

Power Spectral Density (PSD)

$S_{\ddot{x}\ddot{x}}(f)$

Filtering

IFFT

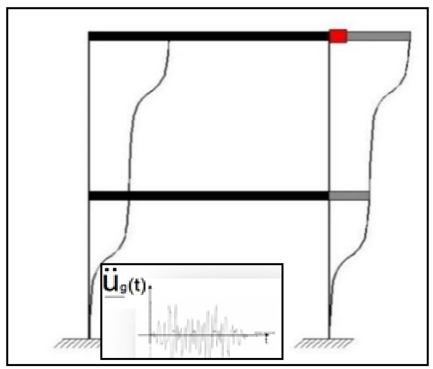
Correlation function

$R_{\ddot{x}\ddot{x}}(\tau)$

Hilbert Transform

Analytical signal

$A(\tau)$, $\theta(\tau)$



EASD
European Association
for Structural Dynamics

EURODYN 2020
XI International Conference on
Structural Dynamics

23-26 November 2020 - Athens, Greece

HYBRID METHODS

Future Developments

ϕ modal shapes

ζ damping ratios

f frequencies

$\ddot{x}(t)$
Acquisition of output signals

~~**Welch's Method**~~

~~*Power Spectral Density (PSD)*~~
~~$S_{\ddot{x}\ddot{x}}(f)$~~

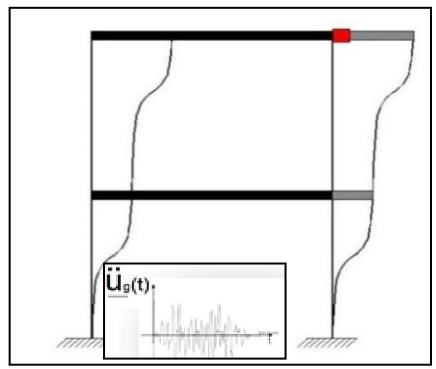
Filtering

IFFT

Correlation function
$R_{\ddot{x}\ddot{x}}(\tau)$

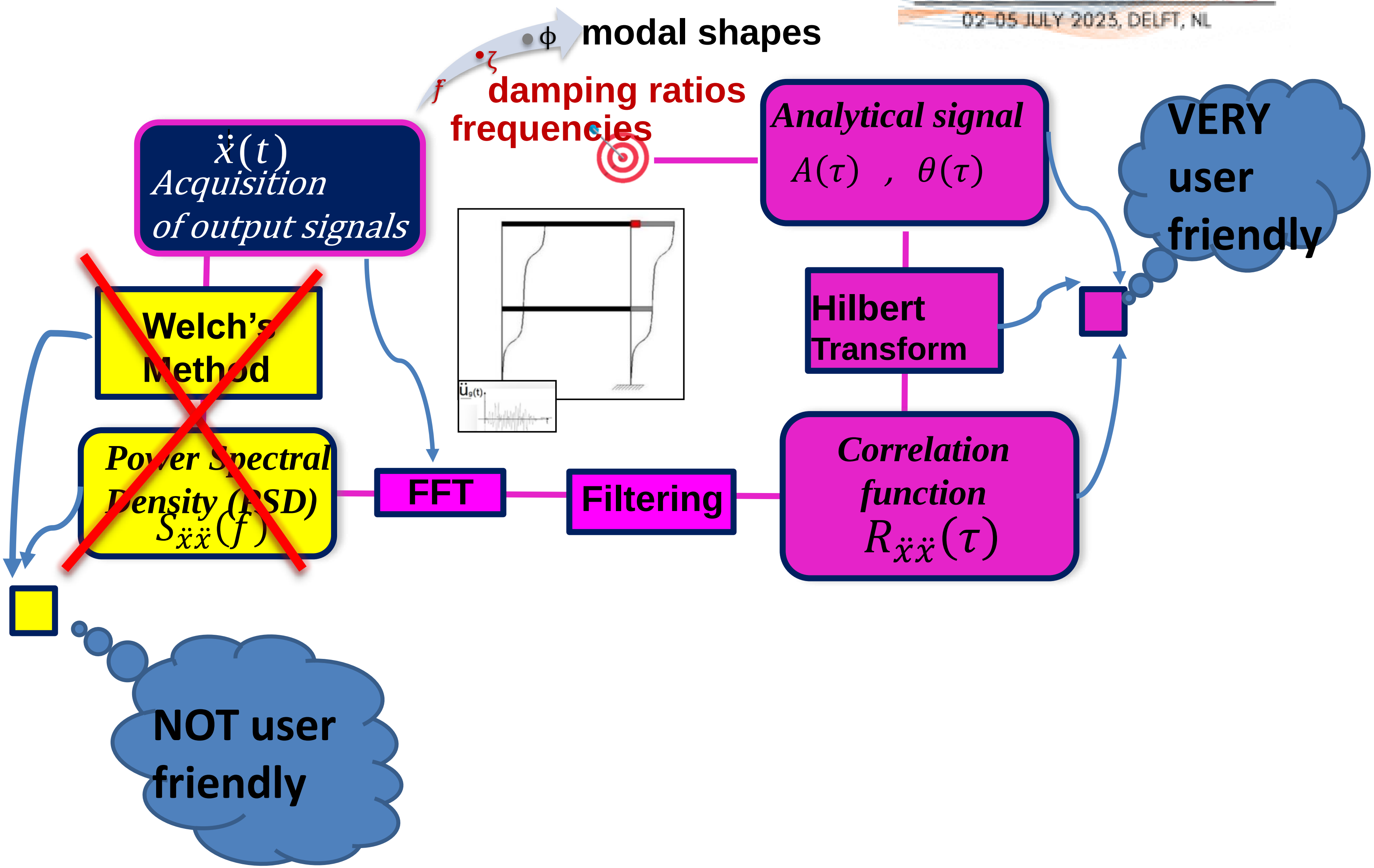
Hilbert Transform

Analytical signal
$A(\tau)$, $\theta(\tau)$



Current Developments

EURODYN 2023
XII International Conference on Structural Dynamics
02-05 JULY 2023, DELFT, NL



AIM: **PROPOSED METHOD**

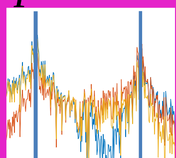
Structural **dynamic identification through a user friendly procedure!**

$\mathbf{X}(t)$

Acquisition of output signals

Fourier Transform

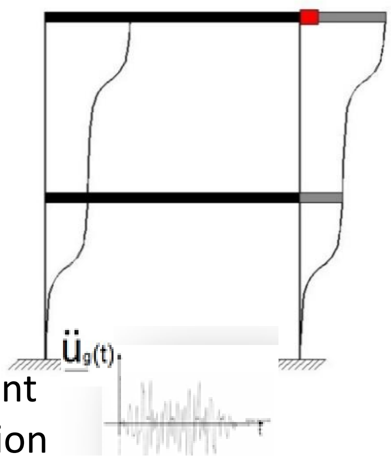
Selection of the peaks for filters



Correlation function

$\mathbf{R}_{\mathbf{X}}(\tau)$ $\mathbf{R}_{\mathbf{X}^{filt}}(\tau)$

$f_i, \ \zeta_i$



Ambient Vibration

Modal Shapes

ϕ_i

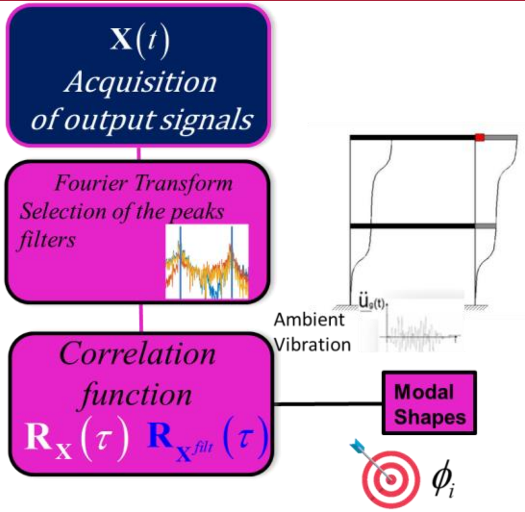
Analytical signal

$A(\tau), \ \theta(\tau)$

Hilbert Transform

Correlation function in Modal Space

$\mathbf{R}_{\mathbf{Y}}(\tau)$

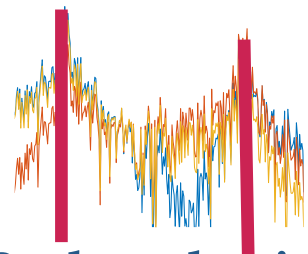


FIRST GOAL MODAL SHAPES ϕ_i

Acquisition of output signals $\mathbf{X}(t)$

FT

$$\ddot{X}_i(\omega) = \int_{-\infty}^{\infty} e^{-i\omega t} \ddot{X}_i(t)\,dt$$



Peaks selection

$$\ddot{X}_i^{(filt\ k)}(t)$$

$$\mathbf{R}_{\mathbf{X}^{filt}}(\tau)$$

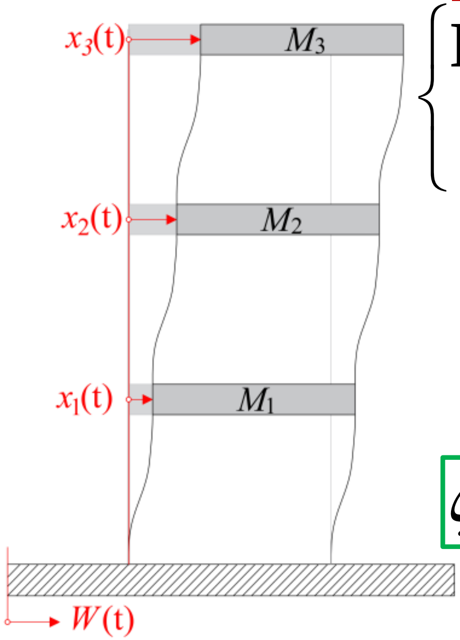
$$\mathbf{R}_{\mathbf{X}}(\tau)$$

$$\frac{R_{\ddot{X}_i^{(filt\ k)}\ddot{X}_1^{(filt\ k)}}(0)}{R_{\ddot{X}_1^{(filt\ k)}}(0)} \approx \frac{\phi_{ik}}{\phi_{1k}}$$

ϕ_i

$$\mathbf{\Phi} = \begin{bmatrix} 1 & 1 & \dots & 1 \\ \frac{\phi_{21}}{\phi_{11}} & \frac{\phi_{22}}{\phi_{12}} & \dots & \frac{\phi_{2m}}{\phi_{1m}} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{\phi_{n1}}{\phi_{11}} & \frac{\phi_{n2}}{\phi_{12}} & \dots & \frac{\phi_{nm}}{\phi_{1m}} \end{bmatrix}$$

Numerical Application: 3DOF System



$$\begin{cases} \mathbf{M}\ddot{\mathbf{X}}(t)+\mathbf{C}\dot{\mathbf{X}}(t)+\mathbf{K}\mathbf{X}(t)=-\mathbf{M}\mathbf{V}W(t) \\ \mathbf{X}(0)=\mathbf{0}; \quad \dot{\mathbf{X}}(0)=\mathbf{0}; \end{cases}$$

$$M_1 = 0.6193 \text{ kg}$$
$$M_2 = 0.5974 \text{ kg}$$
$$M_3 = 0.5647 \text{ kg}$$

$$k_1 = k_2 = k_3 = 0.6\cdot 10^3 \text{ N/m}$$

$$\zeta_1 = 0.006; \quad \zeta_2 = 0.007; \quad \zeta_3 = 0.005;$$

$$\bar{f}_1 = f_1\sqrt{1-\zeta_1^2}$$

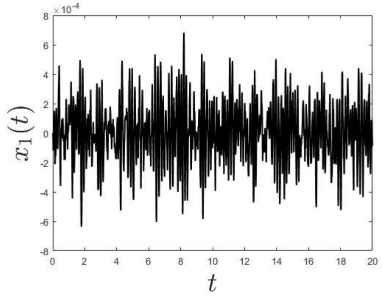
$$\bar{f}_1 = 2.2740Hz; \quad \bar{f}_2 = 6.2888Hz; \quad \bar{f}_3 = 9.0638Hz;$$

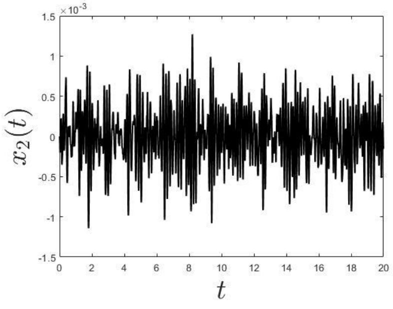
Number of record: 100
Time of recording: 60 s
Sampling frequency: 1000 Hz

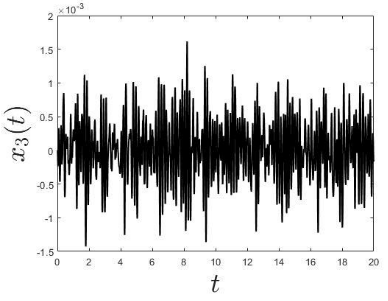
W(t) is a zero mean

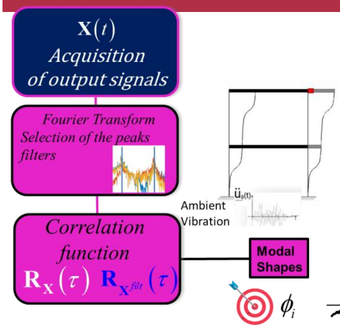
Gaussian white noise process of power spectral density $S_0 = 9*10^{-5}$ m^2/s^3

Signal Responses



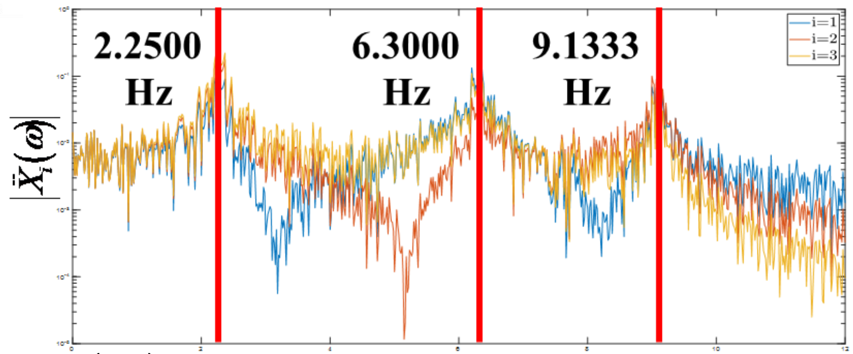


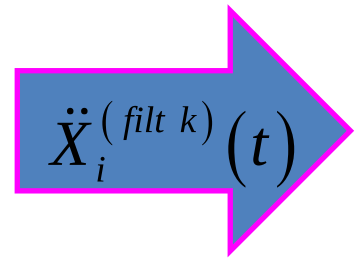




Numerical Application: 3DOF System

FFT and Peaks selection



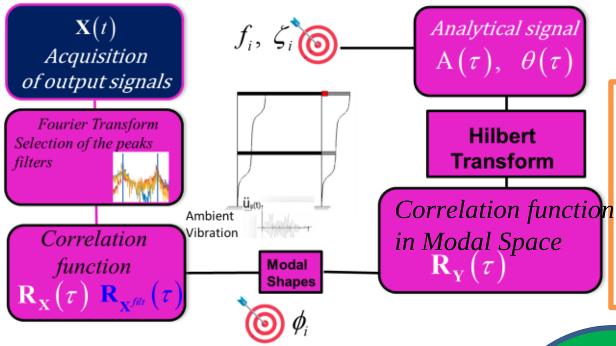


$\mathbf{R}_{\ddot{\mathbf{X}}^{filt}}(\tau)$

$$\frac{R_{\ddot{X}_i^{(filt\ k)}\ddot{X}_1^{(filt\ k)}}(0)}{R_{\ddot{X}_1^{(filt\ k)}}(0)} \approx \frac{\phi_{ik}}{\phi_{1k}}$$

$\mathbf{\Phi}$

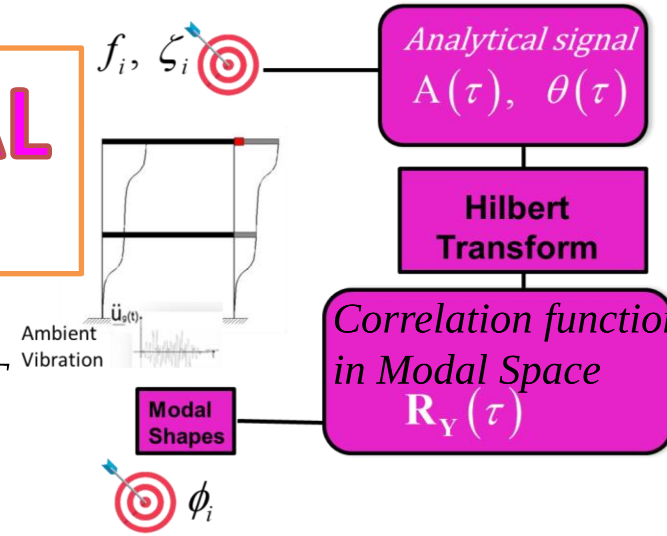
	Exact	Proposed method	Discrepancy [%]	FDD	Discrepancy [%]	SSI	Discrepancy [%]
ϕ_{11}	1.0000	1.0000	**0.0000**	1.0000	**0.0000**	1.0000	**0.0000**
ϕ_{21}	1.7893	1.7931	**0.2148**	1.7796	**0.5414**	1.8097	**1.1393**
ϕ_{31}	2.2148	2.2209	**0.2731**	2.1997	**0.6846**	2.2451	**1.3644**
ϕ_{12}	1.0000	1.0000	**0.0000**	1.0000	**0.0000**	1.0000	**0.0000**
ϕ_{22}	0.3884	0.3814	**1.7773**	0.3880	**0.0785**	0.4037	**3.9463**
ϕ_{32}	-0.8271	-0.8263	**0.0893**	-0.8270	**0.0038**	-0.8287	**0.2040**
ϕ_{13}	1.0000	1.0000	**0.0000**	1.0000	**0.0000**	1.0000	**0.0000**
ϕ_{23}	-1.3476	-1.3621	**1.0705**	-1.3734	**1.9091**	-1.3415	**0.4541**
ϕ_{33}	0.6566	0.6657	**1.3949**	0.6740	**2.6575**	0.6527	**0.5938**



PROPOSED METHOD

SECOND GOAL

f_i, ζ_i



ONCE Φ

$R_X(\tau)$

$$R_Y(\tau) = \Phi^{-1} R_X(\tau) \Phi^{-T}$$

Modal space

$$R_Y(\tau) = \begin{bmatrix} R_{Y_1Y_1}(\tau) & R_{Y_1Y_2}(\tau) & R_{Y_1Y_3}(\tau) \\ R_{Y_2Y_1}(\tau) & R_{Y_2Y_2}(\tau) & R_{Y_2Y_3}(\tau) \\ R_{Y_3Y_1}(\tau) & R_{Y_3Y_2}(\tau) & R_{Y_3Y_3}(\tau) \end{bmatrix}$$

Auto-Correlation functions $R_{Y_jY_j}(\tau)$ in the modal space are monocomponent and then

have a **well-behaved**

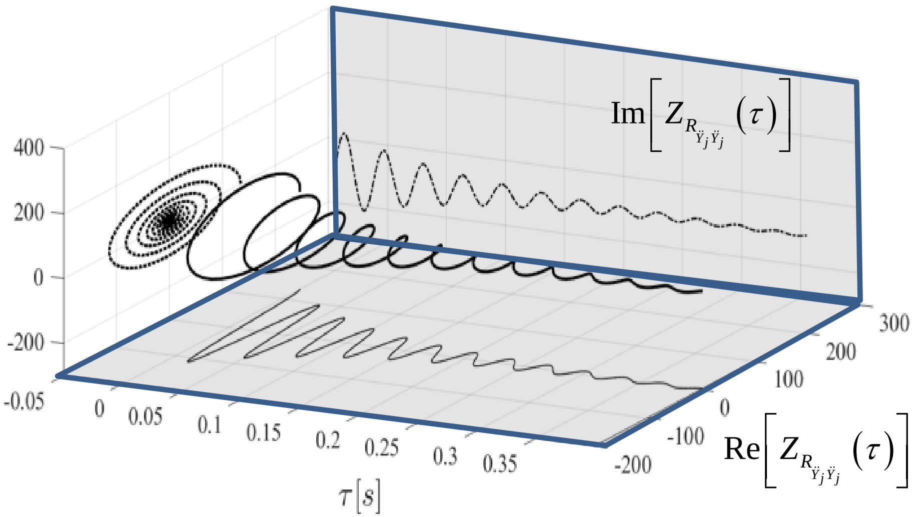
Hilbert Transform

David Hilbert (1862-1943)

PROPOSED METHOD

Analytical signal

$$Z_{Y_jY_j}(\tau) = R_{Y_jY_j}(\tau) + i\,\hat{R}_{Y_jY_j}(\tau)$$



$$R_{Y_jY_j}(\tau) = E_j\; e^{-2\pi f_j \zeta_1 \tau} \sin\left(2\pi \bar{f}_j \tau + \varphi_j\right)$$

$$\hat{R}_{Y_jY_j}(\tau) = -E_j\; e^{-2\pi f_j \zeta_j \tau} \cos\left(2\pi \bar{f}_j \tau + \varphi_j\right)$$

Hilbert Transform

$$\hat{f}(t) = \frac{1}{\pi} \wp \int \frac{f(\tau)}{t-\tau} d\tau$$

$\wp$ pricipal value

Analytical signal properties

$$Z_{Y_jY_j}(\tau) = A_j(\tau) \exp\left[i\theta_j(\tau)\right]$$

$$\theta_j(\tau) = \arctan\left[\hat{R}_{Y_jY_j}(\tau) / R_{Y_jY_j}(\tau)\right]$$

$$A_j(\tau) = \sqrt{R_{Y_jY_j}(\tau)^2 + \hat{R}_{Y_jY_j}(\tau)^2}$$

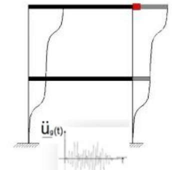
PROPOSED METHOD

$f_i,\ \zeta_i$

Analytical signal $A(\tau),\ \theta(\tau)$

Hilbert Transform

Correlation function in Modal Space $\mathbf{R}_{\mathbf{Y}}(\tau)$



Analytical signal $Z_{Y_jY_j}(\tau) = R_{Y_jY_j}(\tau) + i\,\hat{R}_{Y_jY_j}(\tau)$

$$R_{Y_jY_j}(\tau) = E_j\ e^{-2\pi f_j\zeta_1\tau}\sin\left(2\pi \bar{f}_j\tau + \varphi_j\right)$$

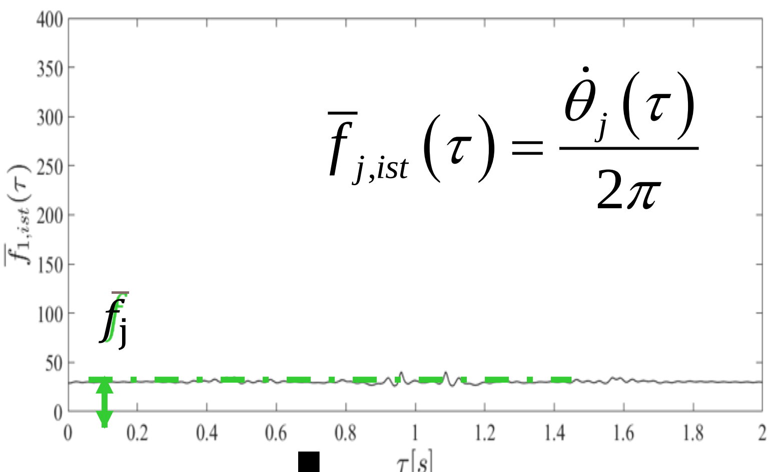
$$\hat{R}_{Y_jY_j}(\tau) = -E_j\ e^{-2\pi f_j\zeta_j\tau}\cos\left(2\pi \bar{f}_j\tau + \varphi_j\right)$$

Analytical signal properties $Z_{Y_jY_j}(\tau) = A_j(\tau)\exp\left[i\theta_j(\tau)\right]$

$$\theta_j(\tau) = \arctan\left[\hat{R}_{Y_jY_j}(\tau) / R_{Y_jY_j}(\tau)\right] \qquad A_j(\tau) = \sqrt{R_{Y_jY_j}(\tau)^2 + \hat{R}_{Y_jY_j}(\tau)^2}$$

- **Phase** $\theta_j(\tau) = 2\pi \bar{f}_{j,ist}\tau + \varphi_j$ → $\bar{f}_j$

- **Amplitude** $A_j(\tau) = E_j\ e^{-2\pi f_j\zeta_j\tau}$ → ζ_j



$$\bar{f}_j = E[\bar{f}_{j,ist}(\tau)]$$

Proposed Method

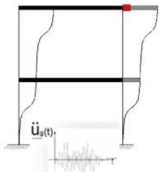
Estimation of Dynamic parameters

$f_i,\ \zeta_i$

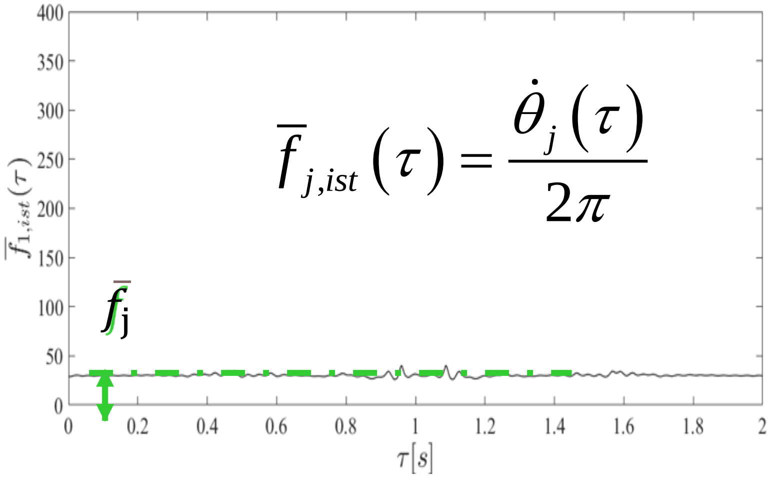
Analytical signal $A(\tau),\ \theta(\tau)$

Hilbert Transform

Correlation function in Modal Space $\mathbf{R_Y}(\tau)$



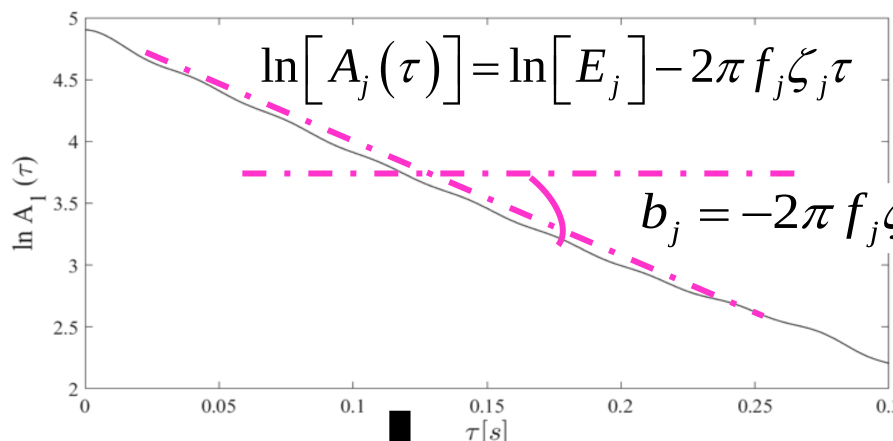
- **Phase** $\theta_j(\tau) = 2\pi \bar{f}_{j,ist}\tau + \varphi_j$



$$\bar{f}_{j,ist}(\tau) = \frac{\dot{\theta}_j(\tau)}{2\pi}$$

$$\bar{f}_j = E[\bar{f}_{j,ist}(\tau)]$$

- **Amplitude** $A_j(\tau) = E_j\, e^{-2\pi f_j \zeta_j \tau}$



$$\ln[A_j(\tau)] = \ln[E_j] - 2\pi f_j \zeta_j \tau$$

$$b_j = -2\pi f_j \zeta_j$$

$$\zeta_j = \sqrt{\frac{b_j^2}{b_j^2 + 4\pi^2 \bar{f}_j^2}}$$

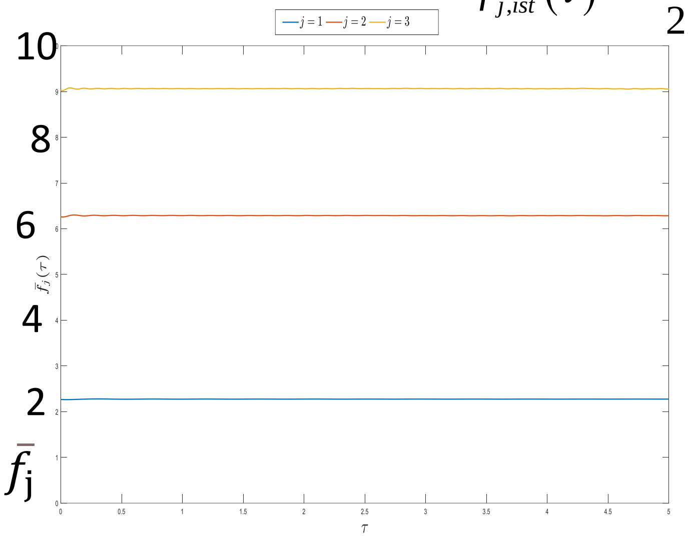
ζ_j and b_j ➡ f_j

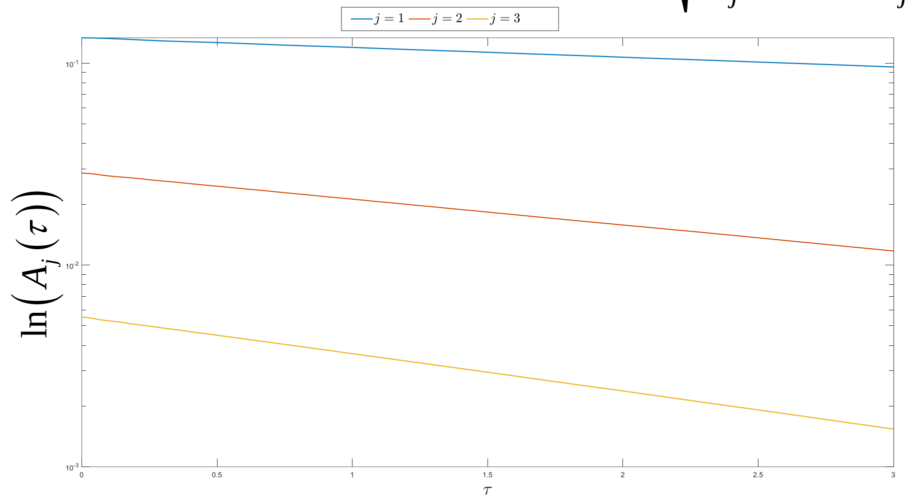
$f_i,\ \zeta_i$

Numerical Application: 3DOF System

$$\bar{f}_{j,ist}(\tau) = \frac{\dot{\theta}_j(\tau)}{2\pi}$$

$$\zeta_j = \sqrt{\frac{b_j^2}{b_j^2 + 4\pi^2 \bar{f}_j^2}}$$





DAMPED FREQUENCIES

Exact	Proposed Method	Discrepancy [%]	FDD	Discrepancy [%]	SSI	Discrepancy [%]
2.2740	2.2711	**0.1289**	2.2579	**0.7088**	2.2717	**0.0100**
6.2888	6.2949	**0.0959**	6.2815	**0.1185**	6.2950	**0.0991**
9.0638	9.0582	**0.0616**	9.0276	**0.3996**	9.0579	**0.0642**

DAMPING RATIOS

Exact	Proposed Method	Discrepancy [%]	FDD	Discrepancy [%]	SSI	Discrepancy [%]
0.0060	0.0068	**13.7958**	0.0072	**20.0000**	0.0071	**18.0504**
0.0070	0.0069	**1.4961**	0.0020	**71.1448**	0.0074	**5.2758**
0.0050	0.0058	**16.5222**	0.0038	**24.8019**	0.0060	**20.6779**

What do I mean with **user Friendly**!!!

2 Aspects

1 Aspect

Self made Matlab script to avoid Black Box

Rune Brincker
Understanding **Stochastic Subspace Identification**

The technique involves several steps of «**mysterious mathematics**» very difficult for people with a classical background in structural dynamics
Block Hankel Matrix and….

2 Aspect

It may be used by people who have little to no knowledge of signal processing

FDD Frequency Domain Decomposition

Welch Method

What about Historical Buildings

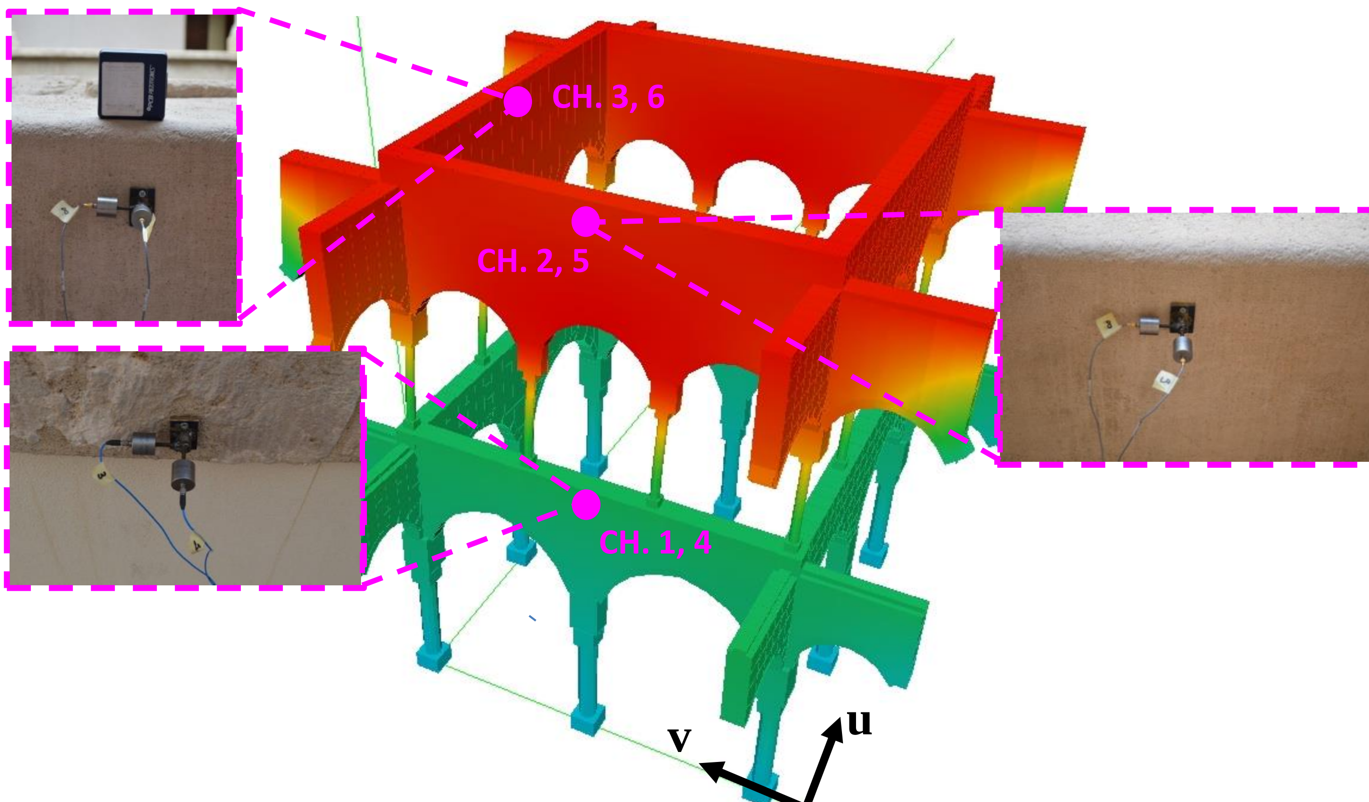
CASE STUDY: CHIARAMONTE PALACE (Palermo)

Located in the marine area of Palermo. Commissioned by Giovanni Chiaramonte and completed in 1307. Now it houses the Rectorate of the University of Palermo.

CASE STUDY: CHIARAMONTE PALACE (Palermo)

- Arab-Norman influences
- Three-story masonry building
- Square plan of about 40x40 m
- Central courtyard (object of this study) distributed over an area of about 400 m^2.
- Height of about 20 m
- Double arcade with ogival arches resting on columns

CASE STUDY: CHIARAMONTE PALACE (Palermo)



Dir. u	LABEL	Dir. v	LABEL
CH. 1	X1	CH. 4	X4
CH. 2	X2	CH. 5	X5
CH. 3	X3	CH. 6	X6

CASE STUDY: CHIARAMONTE PALACE (Palermo)

Piezo-electric accelerometers

PCB 393B04

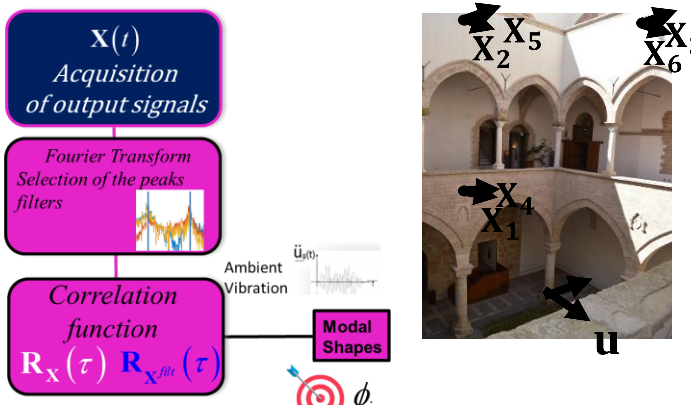
Acquisition unit

PXIe 1082

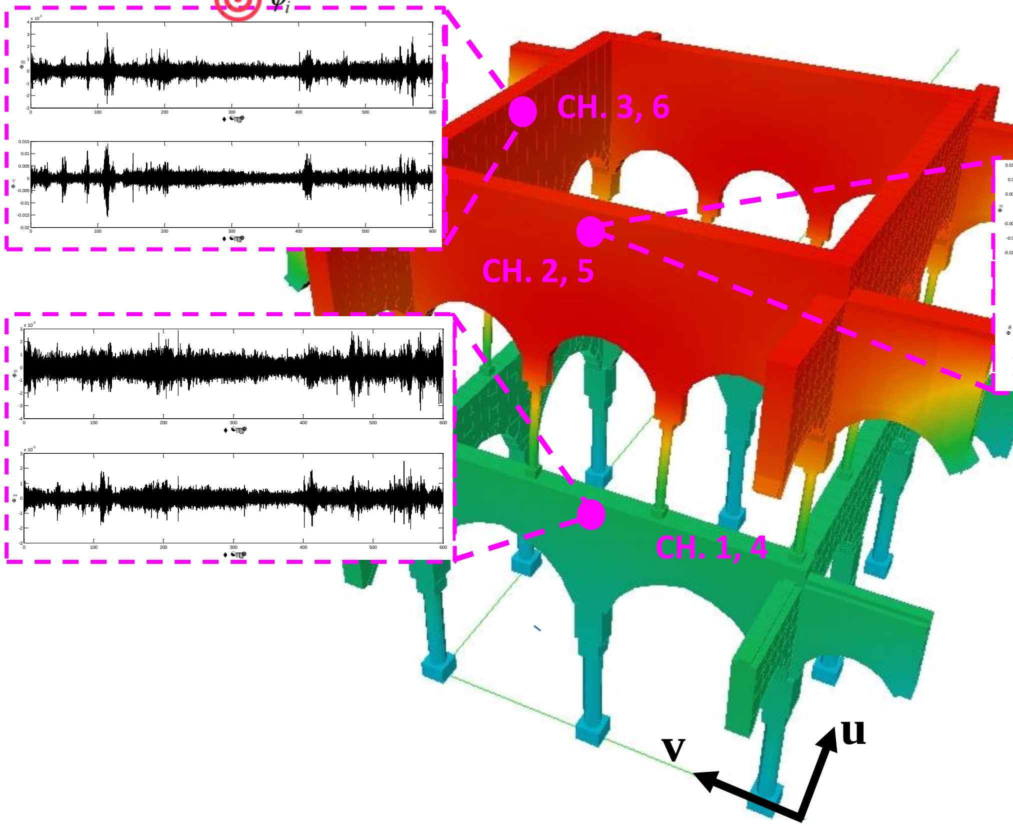
Total duration:
600 s
Sampling frequency: 100 Hz

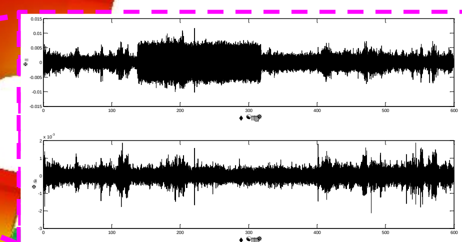
Characteristics of the piezoelectric sensors.

Producer	PCB Piezotronics
Model	PCB 393B04
Sensitivity	1000 mV/g
Measuring range	+/- 5 g
Frequency range	From 0.06 Hz to 450 Hz
Broadband resolution	$3x10^{-6}$ g rms
Mass	50 g

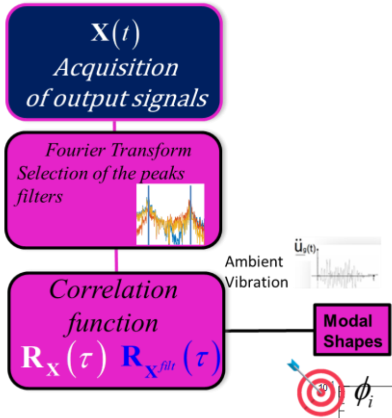


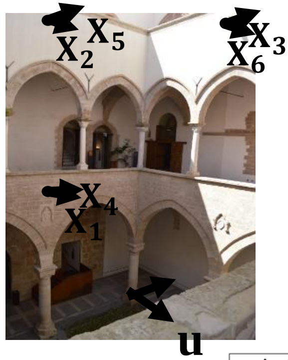
CASE STUDY: CHIARAMONTE PALACE (Palermo)





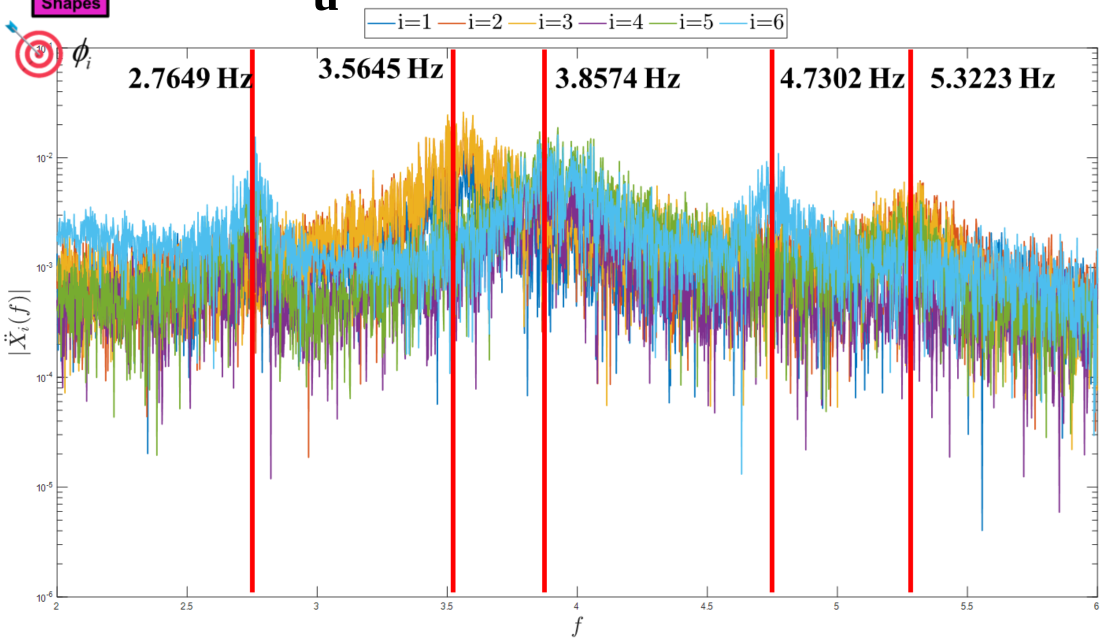
Dir. u	LABEL	Dir. v	LABEL
CH. 1	X1	CH. 4	X4
CH. 2	X2	CH. 5	X5
CH. 3	X3	CH. 6	X6





FFT and Peaks selection

Dir. u	LABEL	Dir. v	LABEL
CH. 1	X1	CH. 4	X4
CH. 2	X2	CH. 5	X5
CH. 3	X3	CH. 6	X6



$$\mathbf{R}_{\mathbf{X}^{filt}}(\tau)$$

$$\frac{R_{\ddot{X}_i^{(filt\ k)}\ddot{X}_1^{(filt\ k)}}(0)}{R_{\ddot{X}_1^{(filt\ k)}}(0)} \approx \frac{\phi_{ik}}{\phi_{1k}}$$

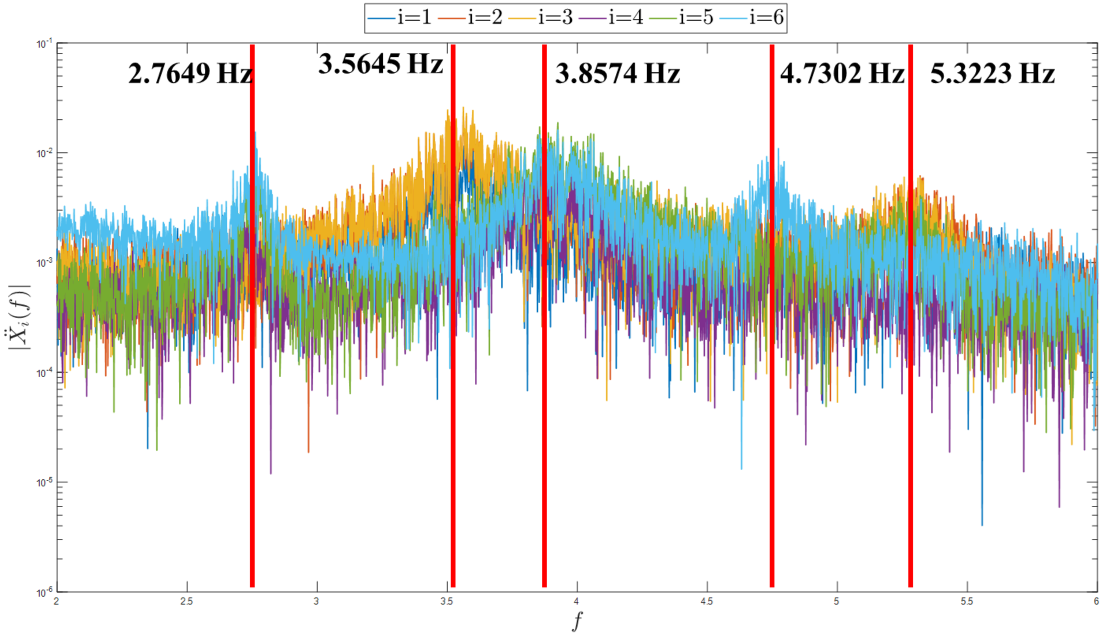
	PM	FDD	SSI
ϕ11	0.1920	0.0234	-
ϕ21	0.0969	-0.0975	-
ϕ31	0.0954	0.0230	-
ϕ41	-0.1457	-0.1990	-
ϕ51	-0.4786	-0.5349	-
ϕ61	-0.8333	-0.8147	-

	PM	FDD	SSI
ϕ12	0.3188	0.3174	0.3038
ϕ22	0.6493	0.6486	0.6381
ϕ32	0.6824	0.6853	0.7042
ϕ42	-0.0375	-0.0298	-0.0103
ϕ52	-0.0958	-0.0859	-0.0621
ϕ62	-0.0237	-0.0259	0.0255

	PM	FDD	SSI
ϕ13	0.1342	0.0911	0.1311
ϕ23	0.2646	0.1778	0.1909
ϕ33	0.2462	0.1570	0.2659
ϕ43	0.3385	0.3538	-0.2576
ϕ53	0.6365	0.6808	-0.7135
ϕ63	0.5759	0.5889	-0.5480

FFT and Peaks selection

Dir. u	LABEL	Dir. v	LABEL
CH. 1	X1	CH. 4	X4
CH. 2	X2	CH. 5	X5
CH. 3	X3	CH. 6	X6



$$\mathbf{R}_{\mathbf{X}^{filt}}(\tau)$$

$$\frac{R_{\ddot{X}_i^{(filt\ k)}\ddot{X}_1^{(filt\ k)}}(0)}{R_{\ddot{X}_1^{(filt\ k)}}(0)} \approx \frac{\phi_{ik}}{\phi_{1k}}$$

	PM	FDD	SSI
ϕ11	0.1920	0.0234	-
ϕ21	0.0969	-0.0975	-
ϕ31	0.0954	0.0230	-
ϕ41	-0.1457	-0.1990	-
ϕ51	-0.4786	-0.5349	-
ϕ61	-0.8333	-0.8147	-

	PM	FDD	SSI
ϕ14	0.2477	0.2494	-
ϕ24	0.2451	0.2561	-
ϕ34	-0.0202	0.0360	-
ϕ44	0.1780	0.2010	-
ϕ54	0.1317	0.1305	-
ϕ64	0.9106	0.9019	-

	PM	FDD	SSI
ϕ12	0.3188	0.3174	0.3038
ϕ22	0.6493	0.6486	0.6381
ϕ32	0.6824	0.6853	0.7042
ϕ42	-0.0375	-0.0298	-0.0103
ϕ52	-0.0958	-0.0859	-0.0621
ϕ62	-0.0237	-0.0259	0.0255

	PM	FDD	SSI
ϕ15	0.4441	0.4012	0.3996
ϕ25	0.5726	0.5753	0.6189
ϕ35	-0.5562	-0.5605	-0.5626
ϕ45	0.0103	0.0656	0.0781
ϕ55	0.3054	0.3333	0.3565
ϕ65	-0.2687	-0.2801	-0.0874

	PM	FDD	SSI
ϕ13	0.1342	0.0911	0.1311
ϕ23	0.2646	0.1778	0.1909
ϕ33	0.2462	0.1570	0.2659
ϕ43	0.3385	0.3538	-0.2576
ϕ53	0.6365	0.6808	-0.7135
ϕ63	0.5759	0.5889	-0.5480

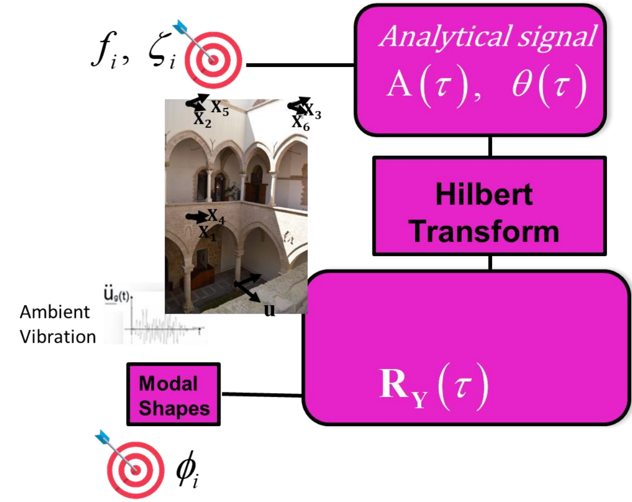
PROPOSED METHOD

ONCE

$\mathbf{\Phi}$

$\mathbf{R_X}(\tau)$

$$\mathbf{R_Y}(\tau) = \mathbf{\Phi}^{+}\mathbf{R_X}(\tau)\left(\mathbf{\Phi}^{T}\right)^{+}$$



$\mathbf{\Phi}^{+} \rightarrow$ Pseudo-inverse of $\mathbf{\Phi}$

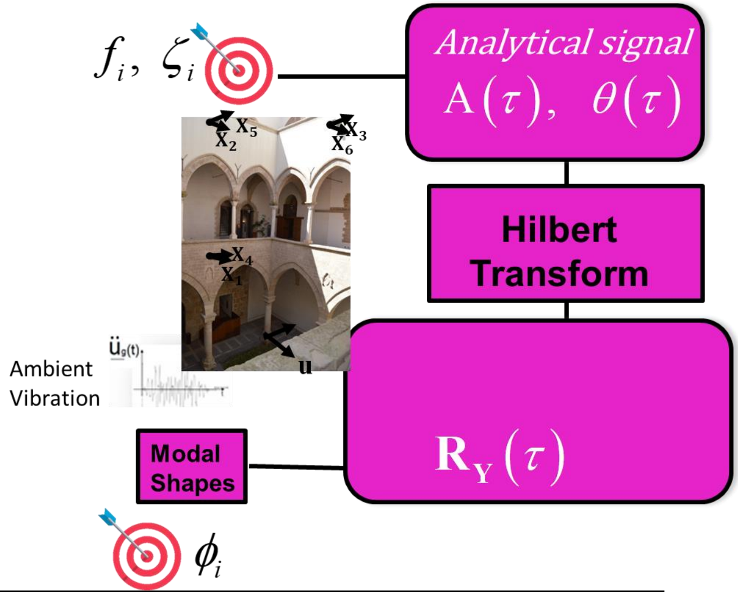
$$\mathbf{R_Y}(\tau) = \begin{bmatrix} R_{Y_1Y_1}(\tau) & R_{Y_1Y_2}(\tau) & R_{Y_1Y_3}(\tau) & R_{Y_1Y_4}(\tau) & R_{Y_1Y_5}(\tau) \\ R_{Y_2Y_1}(\tau) & R_{Y_2Y_2}(\tau) & R_{Y_2Y_3}(\tau) & R_{Y_2Y_4}(\tau) & R_{Y_2Y_5}(\tau) \\ R_{Y_3Y_1}(\tau) & R_{Y_3Y_2}(\tau) & R_{Y_3Y_3}(\tau) & R_{Y_3Y_4}(\tau) & R_{Y_3Y_5}(\tau) \\ R_{Y_4Y_1}(\tau) & R_{Y_4Y_2}(\tau) & R_{Y_4Y_3}(\tau) & R_{Y_4Y_4}(\tau) & R_{Y_4Y_5}(\tau) \\ R_{Y_5Y_1}(\tau) & R_{Y_5Y_2}(\tau) & R_{Y_5Y_3}(\tau) & R_{Y_5Y_4}(\tau) & R_{Y_5Y_5}(\tau) \end{bmatrix}$$

Auto-Correlation functions $R_{Y_jY_j}(\tau)$

have a **well-behaved**

Hilbert Transform

CASE STUDY: CHIARAMONTE PALACE (Palermo)

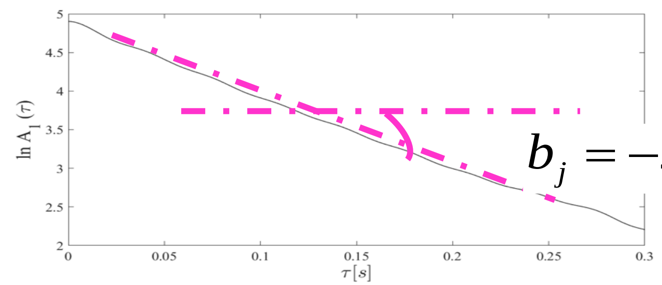


$$Z_{Y_jY_j}(\tau) = R_{Y_jY_j}(\tau) + i\,\hat{R}_{Y_jY_j}(\tau)$$

$$Z_{Y_jY_j}(\tau) = A_j(\tau)\exp\left[i\theta_j(\tau)\right]$$

	PM	FDD	SSI
$\bar{f}_1$	2.7211	2.7648	-
$\bar{f}_2$	3.5509	3.5633	3.5563
$\bar{f}_3$	3.8617	3.8567	3.9200
$\bar{f}_4$	4.7477	4.7295	-
$\bar{f}_5$	5.2937	5.3218	5.2947

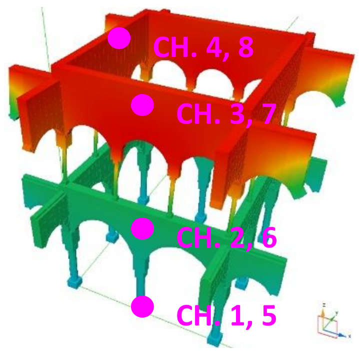
$$\bar{f}_{j,ist}(\tau) = \frac{\dot{\theta}_j(\tau)}{2\pi}$$

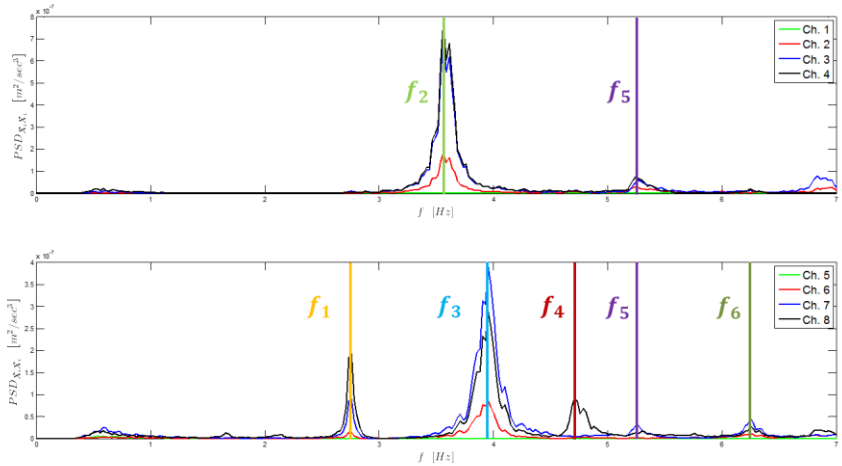


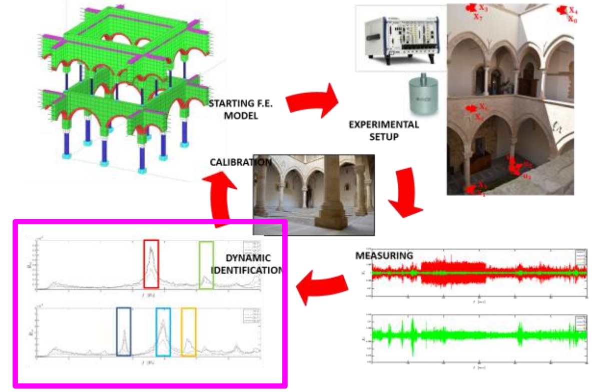
$$b_j = -2\pi f_j \zeta_j$$

Method	ζ_1	ζ_2	ζ_3	ζ_4	ζ_5
FDD	0.96%	2.59%	1.91%	1.73%	1.28%
SSI	-	2.56%	2.35%	-	1.26%
Proposed Method	1.33%	2.40%	2.45%	1.23%	1.31%

SDI: frequencies and damping ratios PREVIOUS TESTS







PREVIOUS TESTS

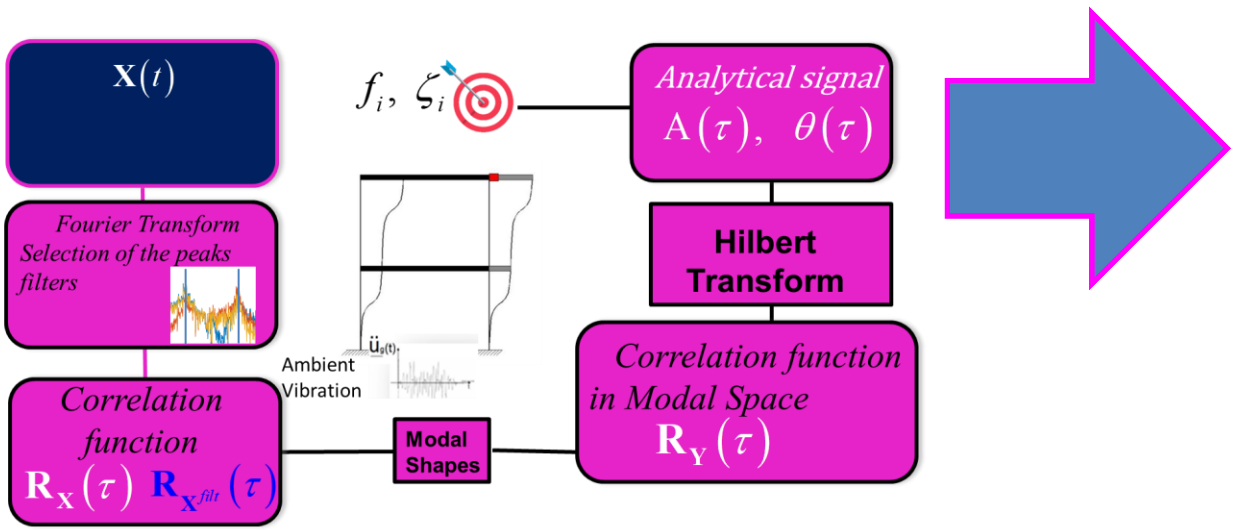
	f_1	f_2	f_3	f_4	f_5
(Hz)	2.755	3.564	3.955	4.719	5.257
	ξ_1	ξ_2	ξ_3	ξ_4	ξ_5
(%)	1.329	2.055	2.223	1.813	1.882

	PM	FDD	SSI
$\bar{f}_1$	2.7211	2.7648	-
$\bar{f}_2$	3.5509	3.5633	3.5563
$\bar{f}_3$	3.8617	3.8567	3.9200
$\bar{f}_4$	4.7477	4.7295	-
$\bar{f}_5$	5.2937	5.3218	5.2947

Method	ζ_1	ζ_2	ζ_3	ζ_4	ζ_5
EFDD	0.96%	2.59%	1.91%	1.73%	1.28%
SSI	-	2.56%	2.35%	-	1.26%
Proposed	1.33%	2.40%	2.45%	1.23%	1.31%

REMARKS

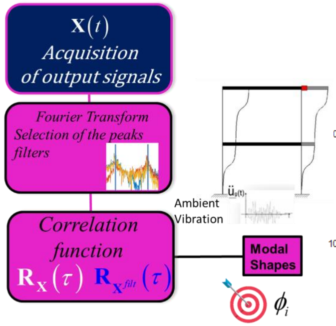
A novel **user friendly** procedure based on applying the Hilbert Transform, to obtain the analytical signal of the ambient response in terms of the correlation function has been proposed. This approach opens the pathway for a monitoring system that is user friendly and can be used by people who have little to no knowledge of signal processing and stochastic analysis such as those who are responsible for the maintenance of a city's ***Historical Buildings***, just by looking at time domain records!



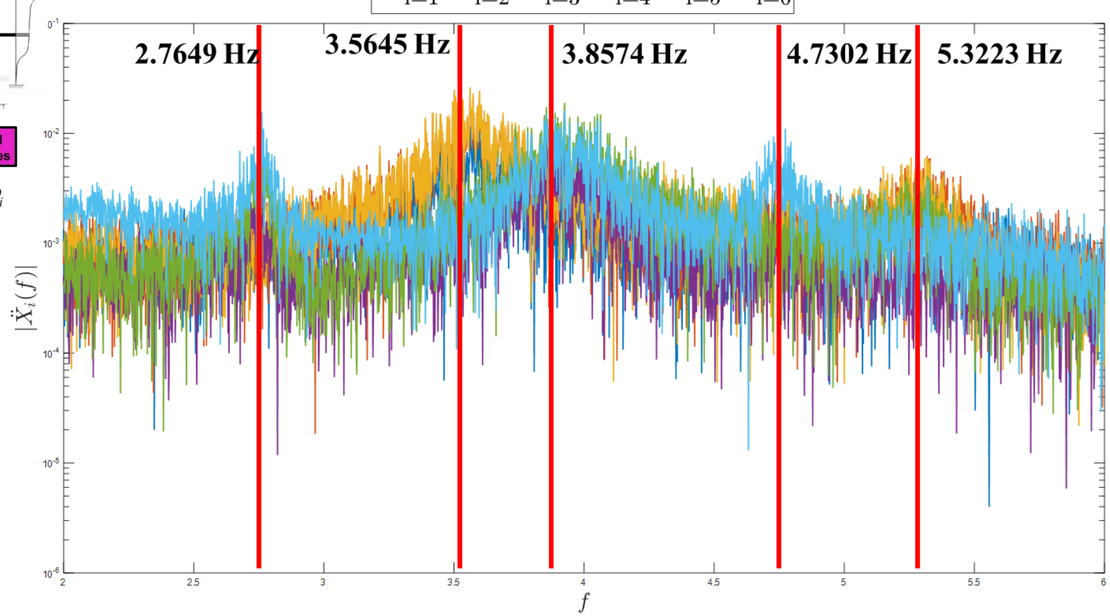
Matlab command

Future Developments

Not well-spaced frequency systems



FFT and Peaks selection



$$\mathbf{R}_{\mathbf{X}^{filt}}(\tau)$$

$$\frac{R_{\ddot{X}_i^{(filt\ k)}\ddot{X}_1^{(filt\ k)}}(0)}{R_{\ddot{X}_1^{(filt\ k)}}(0)} \approx \frac{\phi_{ik}}{\phi_{1k}}$$

Dir. u	LABEL	Dir. v	LABEL
CH. 1	X1	CH. 4	X4
CH. 2	X2	CH. 5	X5
CH. 3	X3	CH. 6	X6

	1	2	3	4	5
Type	Butterworth	Butterworth	Butterworth	Butterworth	Butterworth
Order	8	8	8	8	8
Initial frequency of the passband [Hz]	2.7616	3.5611	3.8541	4.7269	5.3189
Final frequency of the passband [Hz]	2.7682	3.5678	3.8608	4.7336	5.3256

MODAL SHAPES

CASE STUDY: CHIARAMONTE PALACE (Palermo)

	PM	FDD	SSI
ϕ11	0.1920	0.0234	-
ϕ21	0.0969	-0.0975	-
ϕ31	0.0954	0.0230	-
ϕ41	-0.1457	-0.1990	-
ϕ51	-0.4786	-0.5349	-
ϕ61	-0.8333	-0.8147	-

	PM	FDD	SSI
ϕ12	0.3188	0.3174	0.3038
ϕ22	0.6493	0.6486	0.6381
ϕ32	0.6824	0.6853	0.7042
ϕ42	-0.0375	-0.0298	-0.0103
ϕ52	-0.0958	-0.0859	-0.0621
ϕ62	-0.0237	-0.0259	0.0255

	PM	FDD	SSI
ϕ13	0.1342	0.0911	0.1311
ϕ23	0.2646	0.1778	0.1909
ϕ33	0.2462	0.1570	0.2659
ϕ43	0.3385	0.3538	-0.2576
ϕ53	0.6365	0.6808	-0.7135
ϕ63	0.5759	0.5889	-0.5480

	PM	FDD	SSI
ϕ14	0.2477	0.2494	-
ϕ24	0.2451	0.2561	-
ϕ34	-0.0202	0.0360	-
ϕ44	0.1780	0.2010	-
ϕ54	0.1317	0.1305	-
ϕ64	0.9106	0.9019	-

	PM	FDD	SSI
ϕ15	0.4441	0.4012	0.3996
ϕ25	0.5726	0.5753	0.6189
ϕ35	-0.5562	-0.5605	-0.5626
ϕ45	0.0103	0.0656	0.0781
ϕ55	0.3054	0.3333	0.3565
ϕ65	-0.2687	-0.2801	-0.0874

	PM	FDD	SSI
ϕ11	1.0000	1.0000	-
ϕ21	0.5046	-4.1669	-
ϕ31	0.4968	0.9841	-
ϕ41	-0.7588	-8.5099	-
ϕ51	-2.4929	-22.8715	-
ϕ61	-4.3405	-34.8311	-

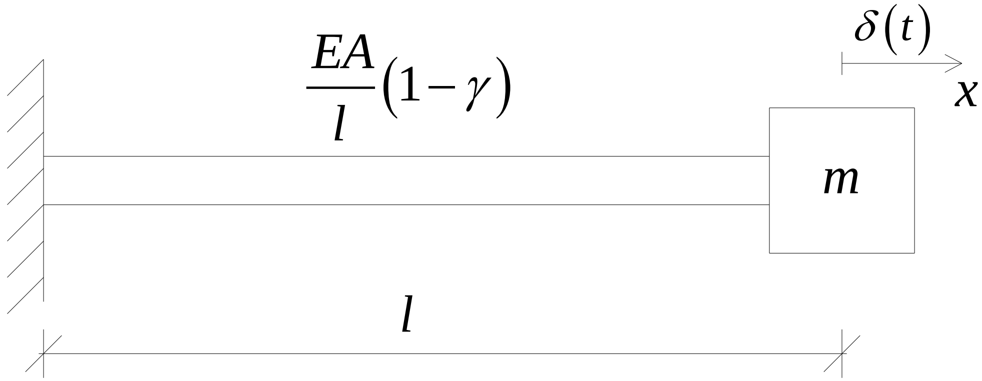
	PM	FDD	SSI
ϕ12	1.0000	1.0000	1.0000
ϕ22	2.0368	2.0433	2.1002
ϕ32	2.1405	2.1589	2.3175
ϕ42	-0.1176	-0.0938	-0.0340
ϕ52	-0.3006	-0.2705	-0.2042
ϕ62	-0.0744	-0.0816	0.0838

	PM	FDD	SSI
ϕ13	1.0000	1.0000	1.0000
ϕ23	1.9709	1.9510	1.4567
ϕ33	1.8338	1.7229	2.0284
ϕ43	2.5215	3.8832	-1.9651
ϕ53	4.7410	7.4725	-5.4431
ϕ63	4.2898	6.4642	-4.1804

	PM	FDD	SSI
ϕ14	1	1	-
ϕ24	0.9894	1.0270	-
ϕ34	-0.0817	0.1444	-
ϕ44	0.7184	0.8059	-
ϕ54	0.5315	0.5232	-
ϕ64	3.6754	3.6168	-

	PM	FDD	SSI
ϕ15	1.0000	1.0000	1.0000
ϕ25	1.2895	1.4340	1.5488
ϕ35	-1.2524	-1.3970	-1.4078
ϕ45	0.0233	0.1635	0.1954
ϕ55	0.6876	0.8307	0.8922
ϕ65	-0.6051	-0.6982	-0.2186

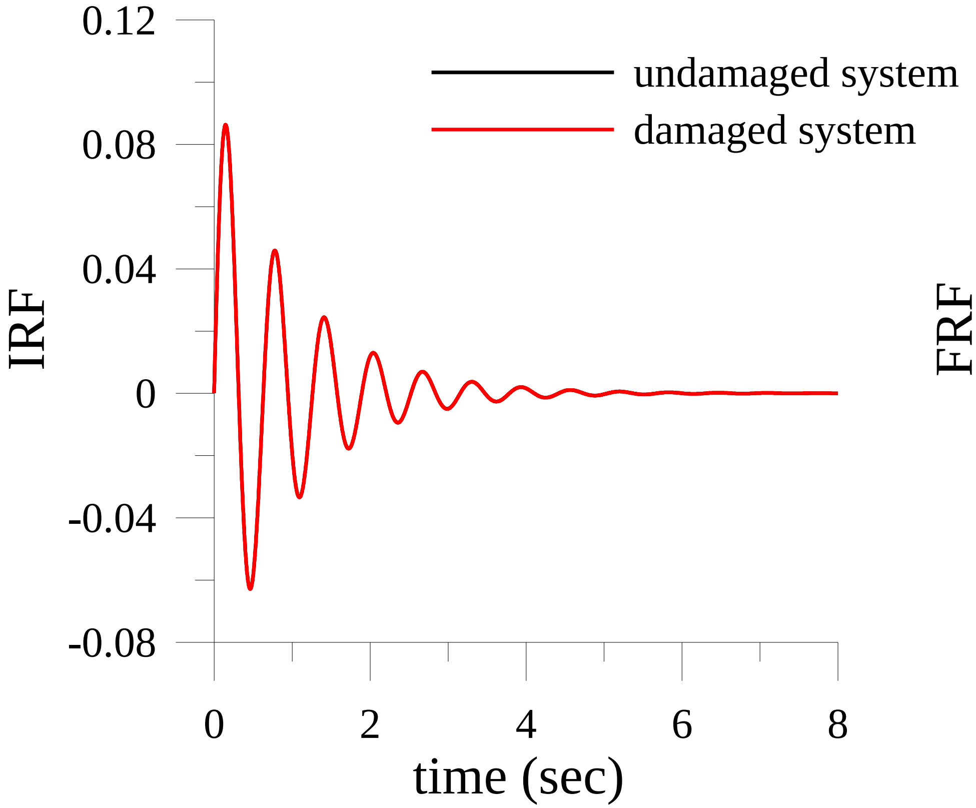
Damage identification SDOF system Statement of the problem

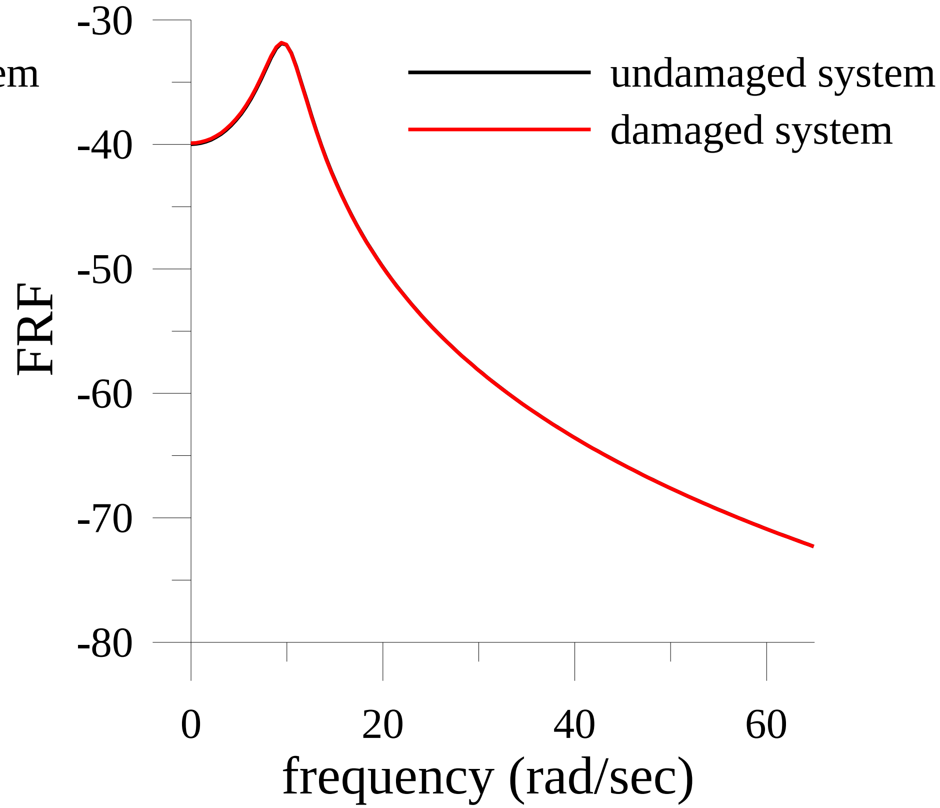


$$\omega_0 = \sqrt{\frac{EA}{ml}} = 10 \text{ rad/sec}$$

$$\Lambda = \zeta_0 \omega_0 = 1 = \text{cost}, \quad \gamma = 0.01$$

$$\ddot{x}(t) + 2\Lambda \dot{x}(t) + (1-\gamma)\omega_0^2 x(t) = \delta(t)$$





Damage Identification SDOF system

Use of Analytical signal

$$y(t) = x(t) + i\hat{x}(t)$$

Analytical Signal

$$\mathrm{HT}\left[x(t)\right] = \hat{x}(t) = \frac{1}{\pi}\wp\int_{-\infty}^{+\infty}\frac{x(\tau)}{t-\tau}d\tau$$

Hilbert transform

$$y(t) = x(t) + i\hat{x}(t) = A(t)\exp[i\theta(t)]$$

$$A(t) = \sqrt{x(t)^2 + \hat{x}(t)^2}$$

Amplitude

$$\theta(t) = \arctan\left[\frac{\hat{x}(t)}{x(t)}\right]$$

Phase

$$\omega_{ist}(t) = \dot{\theta}(t)$$

Instantaneous Frequency

Use of Hilbert Transform and of Analytical Signal

- HT for detecting and quantify system non-linearities.

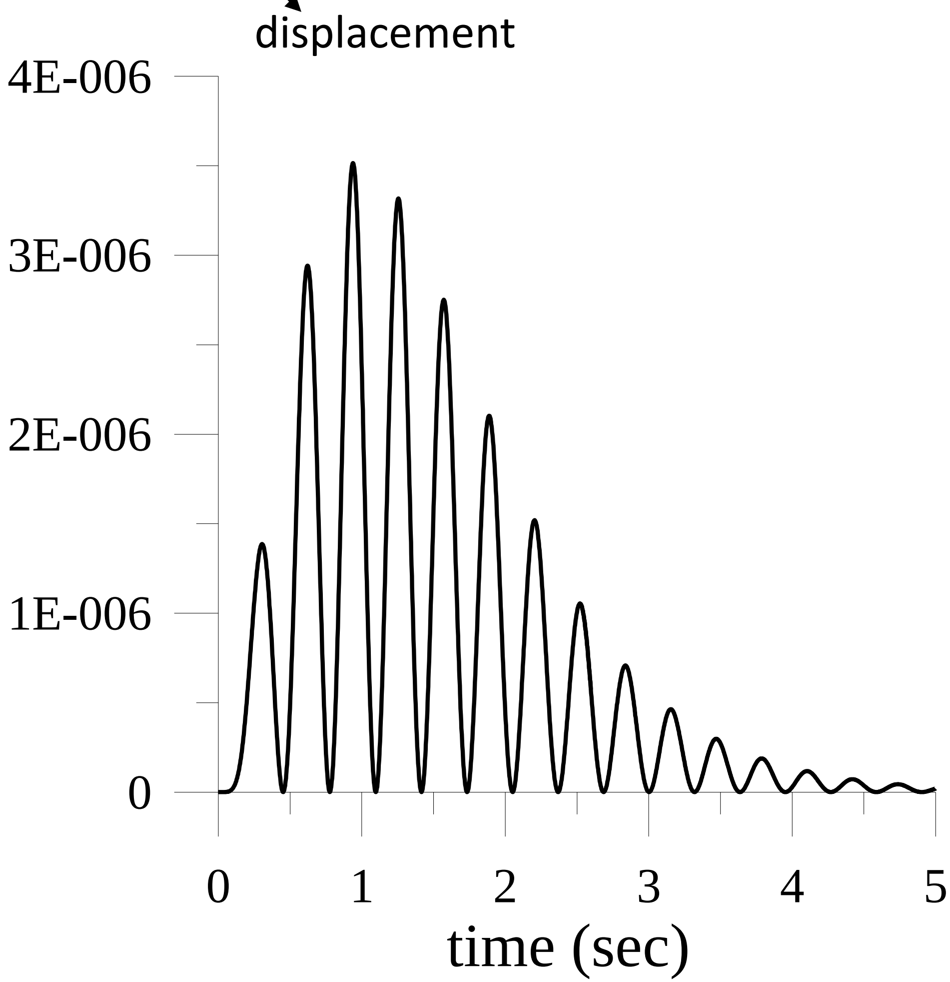
- Analytical signal for the system characterization.

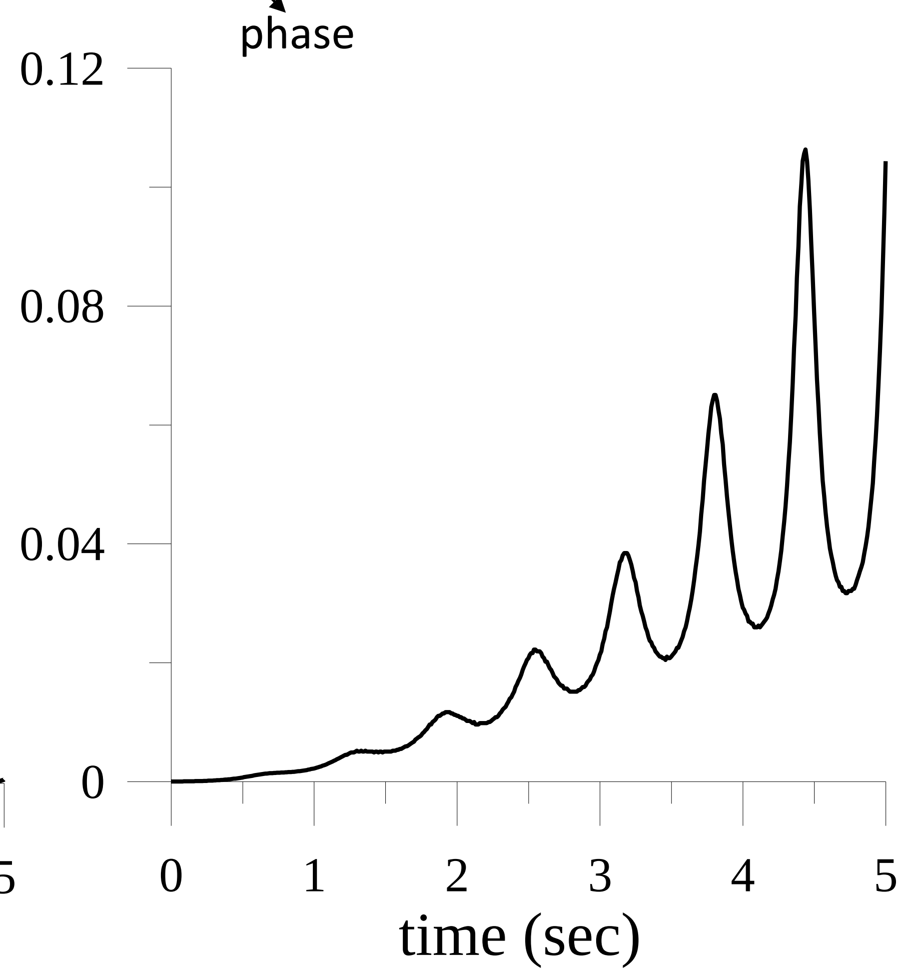
- M. Simon, G.R. Tomlison, (1984) *Journal of Sound and Vibration*, 96.
- G.R. Tomlinson, I. Ahmed, (1987) *Meccanica*, 22.

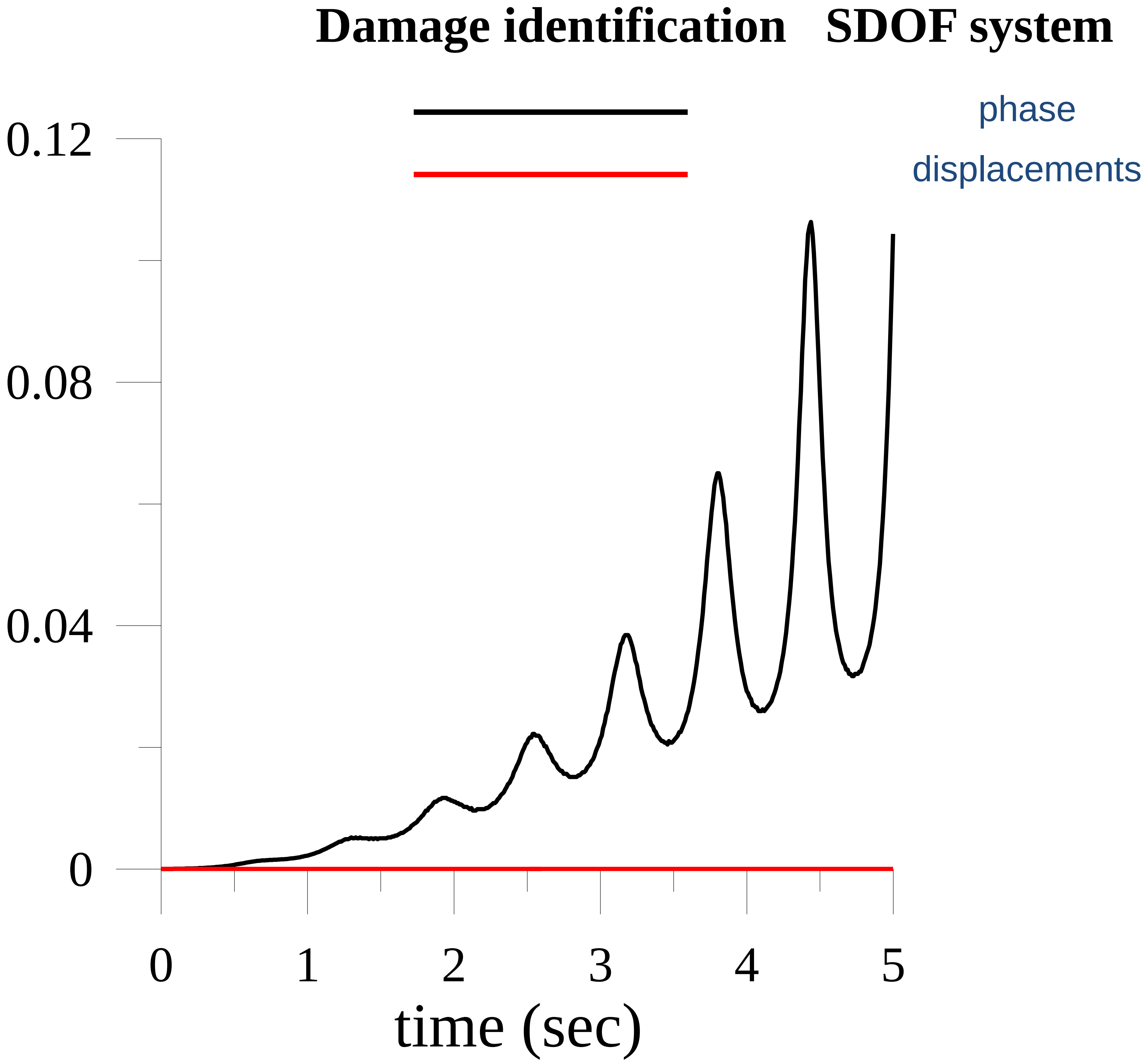
- M. Feldman, (1997) Journal of Sound and Vibration, 208 .
- S. Braun, M. Feldman, (1997) Mechanical Systems and Signal Processing, 11 .

Damage identification SDOF system

$$\left[x^{un}(t) - x^{dm}(t)\right]^2 \qquad \left[\vartheta^{un}(t) - \vartheta^{dm}(t)\right]^2$$






Damage identification SDOF system
phase
displacements
0.12
0.08
0.04
0
0
1
2
3
4
5
time (sec)

Filtering of the response process

PROPOSED METHOD

Acceleration process – Time domain

$$\ddot{\mathbf{X}}(t) = \tilde{\mathbf{\Phi}}\ddot{\mathbf{Q}}(t)$$

$$\ddot{X}_i(t) = \tilde{\phi}_{i1}\ddot{Q}_1(t) + \tilde{\phi}_{i2}\ddot{Q}_2(t) + \ldots + \tilde{\phi}_{in}\ddot{Q}_n(t) = \sum_{j=1}^{n} \tilde{\phi}_{ij}\ddot{Q}_j(t)$$

Acceleration process – Frequency domain

$$\ddot{X}_i(\omega) = \tilde{\phi}_{i1}\ddot{Q}_1(\omega) + \tilde{\phi}_{i2}\ddot{Q}_2(\omega) + \ldots + \tilde{\phi}_{in}\ddot{Q}_n(\omega) = \sum_{j=1}^{n} \tilde{\phi}_{ij}\ddot{Q}_j(\omega)$$

If the frequencies are well-separated, in correspondance of the k-th resonant frequency $\ddot{X}_i(\omega_k) \approx \tilde{\phi}_{ik}\ddot{Q}_k(\omega_k)$

Thus, by filtering the response process around the k-th resonant frequency by using band-pass filters with very little bandwidth

$$\ddot{X}_i^{(filt\ k)}(t) \approx \tilde{\phi}_{ik}\ddot{Q}_k^{(filt\ k)}(t)$$

	1	**2**	**3**
Type	Butterworth	Butterworth	Butterworth
Order	8	8	8
Initial frequency of the passband [Hz]	2.2333	6.2500	9.0333
Final frequency of the passband [Hz]	2.3000	6.3167	9.1000

Correlations of the filtered signals and modal shapes estimation

PROPOSED METHOD

Cross-correlations

$$R_{\ddot{X}_i^{(filt\ k)}\ddot{X}_1^{(filt\ k)}}(\tau) = E\left[\ddot{X}_i^{(filt\ k)}(t)\,\ddot{X}_1^{(filt\ k)}(t+\tau)\right]$$

$$R_{\ddot{X}_i^{(filt\ k)}\ddot{X}_1^{(filt\ k)}}(\tau) \approx E\left[\tilde{\phi}_{ik}\ddot{Q}_k^{(filt\ k)}(t)\,\tilde{\phi}_{1k}\ddot{Q}_k^{(filt\ k)}(t+\tau)\right] = \tilde{\phi}_{ik}\tilde{\phi}_{1k}R_{\ddot{Q}_k^{(filt\ k)}}(\tau)$$

Auto-correlations

$$R_{\ddot{X}_1^{(filt\ k)}}(\tau) = E\left[\ddot{X}_1^{(filt\ k)}(t)\,\ddot{X}_1^{(filt\ k)}(t+\tau)\right]$$

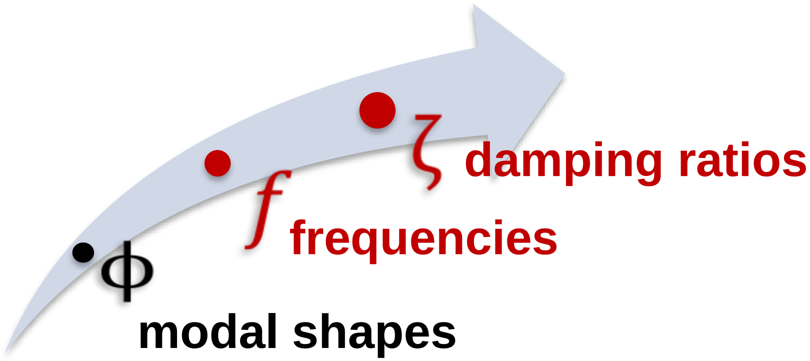
$$R_{\ddot{X}_1^{(filt\ k)}}(\tau) \approx E\left[\tilde{\phi}_{1k}\ddot{Q}_k^{(filt\ k)}(t)\,\tilde{\phi}_{1k}\ddot{Q}_k^{(filt\ k)}(t+\tau)\right] = \tilde{\phi}_{1k}^2 R_{\ddot{Q}_k^{(filt\ k)}}(\tau)$$

Modal shapes estimation

$$\frac{R_{\ddot{X}_i^{(filt\ k)}\ddot{X}_1^{(filt\ k)}}(0)}{R_{\ddot{X}_1^{(filt\ k)}}(0)} \approx \frac{\tilde{\phi}_{ik}\tilde{\phi}_{1k}R_{\ddot{Q}_k^{(filt\ k)}}(0)}{\tilde{\phi}_{1k}^2 R_{\ddot{Q}_k^{(filt\ k)}}(0)} = \frac{\tilde{\phi}_{ik}\tilde{\phi}_{1k}\sigma^2_{\ddot{Q}_k^{(filt\ k)}}}{\tilde{\phi}_{1k}^2\sigma^2_{\ddot{Q}_k^{(filt\ k)}}} = \frac{\tilde{\phi}_{ik}}{\tilde{\phi}_{1k}} \longrightarrow \mathbf{\Phi} = \begin{bmatrix} 1 & 1 & \cdots & 1 \\ \frac{\tilde{\phi}_{21}}{\tilde{\phi}_{11}} & \frac{\tilde{\phi}_{22}}{\tilde{\phi}_{12}} & \cdots & \frac{\tilde{\phi}_{2m}}{\tilde{\phi}_{1m}} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{\tilde{\phi}_{n1}}{\tilde{\phi}_{11}} & \frac{\tilde{\phi}_{n2}}{\tilde{\phi}_{12}} & \cdots & \frac{\tilde{\phi}_{nm}}{\tilde{\phi}_{1m}} \end{bmatrix}$$

Goals:

•Structural **dynamic identification through a user friendly procedure in time domain only!**



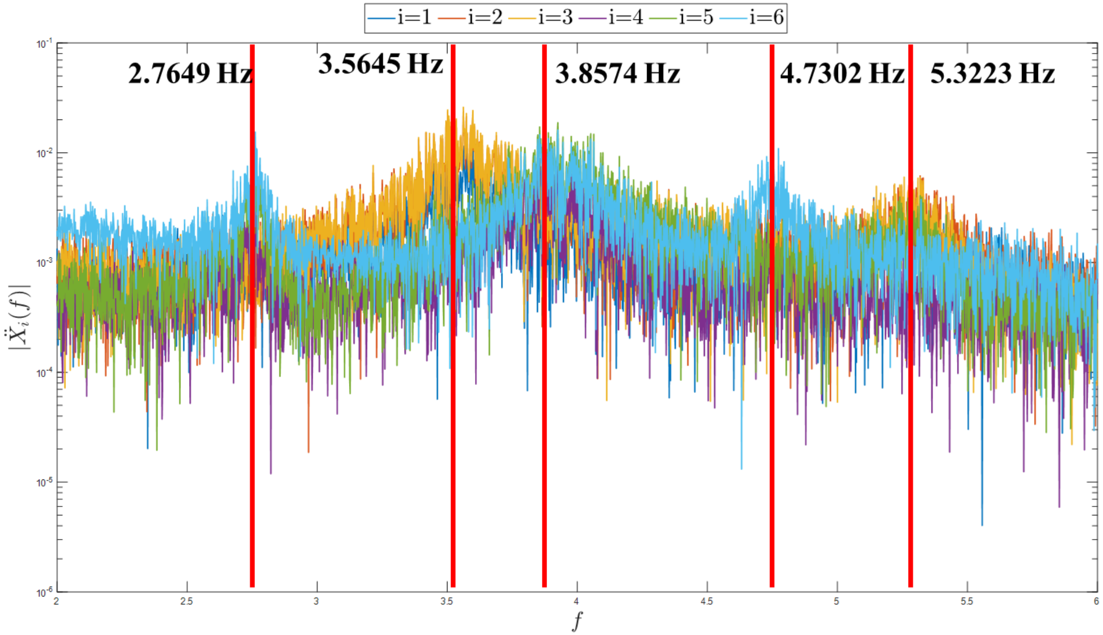
***Proper* for Historical Buildings**

Methodology:

- Ambient vibration tests and **Operational Modal Analysis** (OMA)

FFT and Peaks selection

Dir. u	LABEL	Dir. v	LABEL
CH. 1	X1	CH. 4	X4
CH. 2	X2	CH. 5	X5
CH. 3	X3	CH. 6	X6

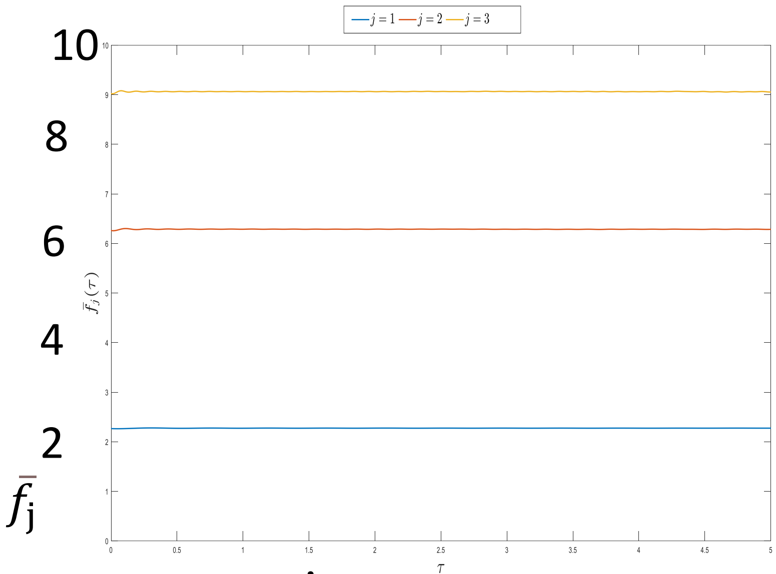


$$\mathbf{R}_{\mathbf{X}^{filt}}(\tau)$$

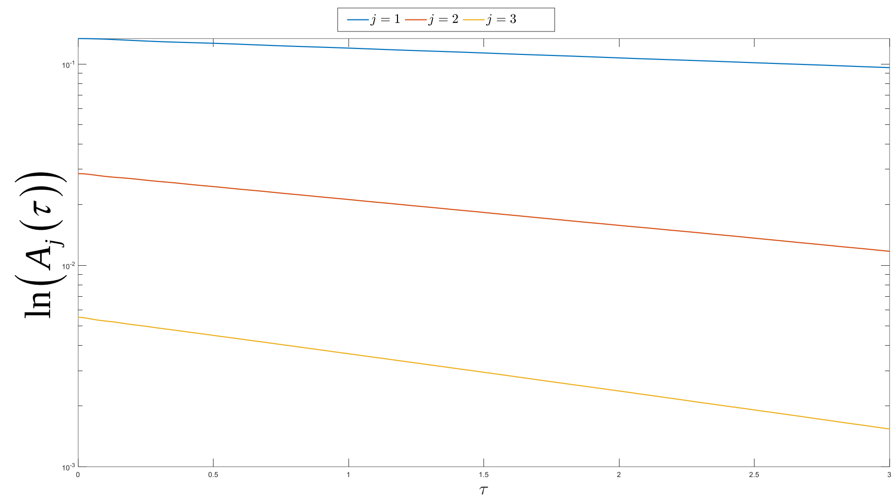
$$\frac{R_{\ddot{X}_i^{(filt\ k)}\ddot{X}_1^{(filt\ k)}}(0)}{R_{\ddot{X}_1^{(filt\ k)}}(0)} \approx \frac{\phi_{ik}}{\phi_{1k}}$$

	Proposed Method			Previous exp results			FEM		
	f	Dir		f	Dir		f	Dir	
1	2.7211	v		2.755	-		2.758	v	
2	3.5509	u		3.564	-		3.556	u	
3	3.8617	v (u)		3.955	-		3.828	v	
4	4.7477	uv		4.719	-		4.62	u	
5	5.2937	u (v)		5.257	-		-	-	

Numerical Application: 3DOF System



$$\overline{f}_{j,ist}(\tau) = \frac{\dot{\theta}_j(\tau)}{2\pi}$$



DAMPING RATIOS		
Exact	**Proposed Method**	**Discrepancy [%]**
0.0060	0.0068	**13.7958**
0.0070	0.0069	**1.4961**
0.0050	0.0058	**16.5222**

DAMPED FREQUENCIES		
Exact	**Proposed Method**	**Discrepancy [%]**
2.2740	2.2711	**0.1289**
6.2888	6.2949	**0.0959**
9.0638	9.0582	**0.0616**

$$\zeta_j = \sqrt{\frac{b_j^2}{b_j^2 + 4\pi^2 \overline{f}_j^{\,2}}}$$

LINK between research and engineering applications of High Level

OMA ⟺ CROWD SENSING

BRIDGE MONITORING

dipartimento di ingegneria unipa
Università degli Studi di Palermo

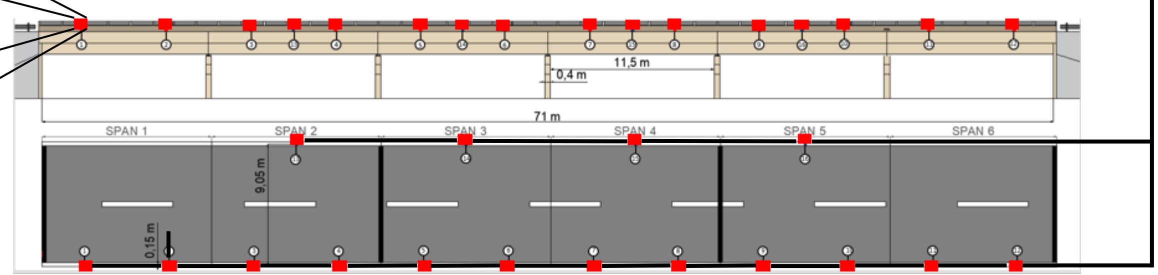
Background

Traditional monitoring technique based on dynamic identification

No artificial input

Structure in operating conditions

Expensive setup

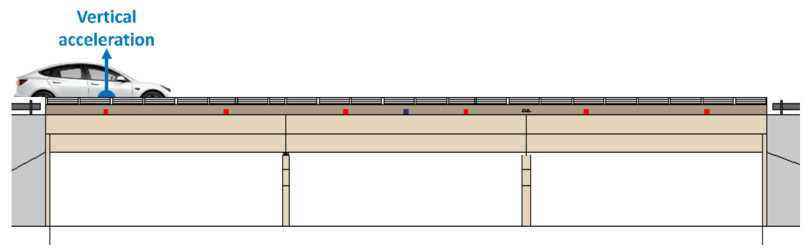


■ Piezoelectric accelerometer

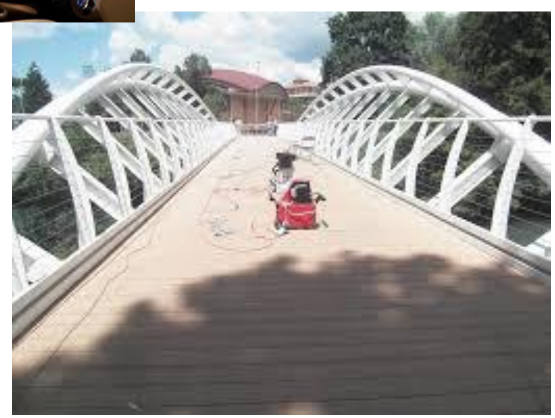
Background

Indirect VBI-based methods

The Vehicle-Bridge Interaction system will allow to monitor civil infrastructures, in an indirect manner, using the recorded responses of the vehicles moving over the bridges



Structure in operating conditions



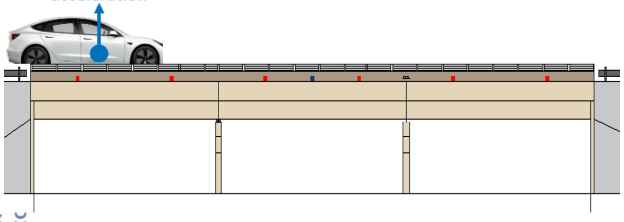
No artificial input

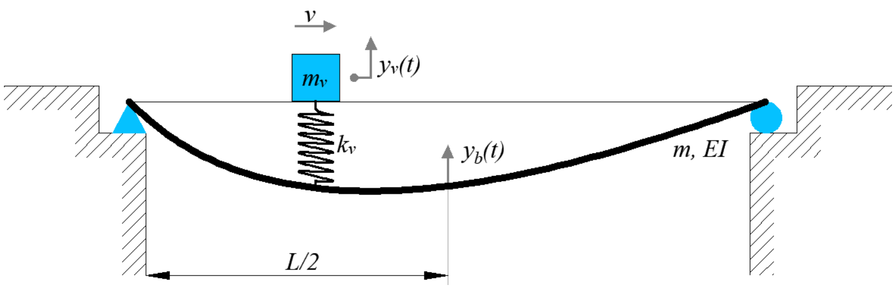
No instrumentations on site

Background

dipartimento di ingegneria unipa
Università degli Studi di Palermo

VBI - Equation of motions





$$
\begin{cases}
m_v \ddot{y}_v + \left(\omega_v^2 m_v\right) y_v - \left[\omega_v^2 m_v \sin\left(\frac{\pi v t}{L}\right)\right] y_b = 0 \\
\frac{mL}{2} \ddot{y}_b + \left[\frac{mL}{2}\omega_b^2 + \omega_v^2 m_v \sin^2\left(\frac{\pi v t}{L}\right)\right] y_b - \left[\omega_v^2 m_v \sin^2\left(\frac{\pi v t}{L}\right)\right] y_v = -m_v g \sin\left(\frac{\pi v t}{L}\right)
\end{cases}
$$

Hypothesis

- First few frequencies taken into account
- Simplified model of the bridge (simply-supported beam)
- No damping
- Vehicle mass much smaller than structural mass

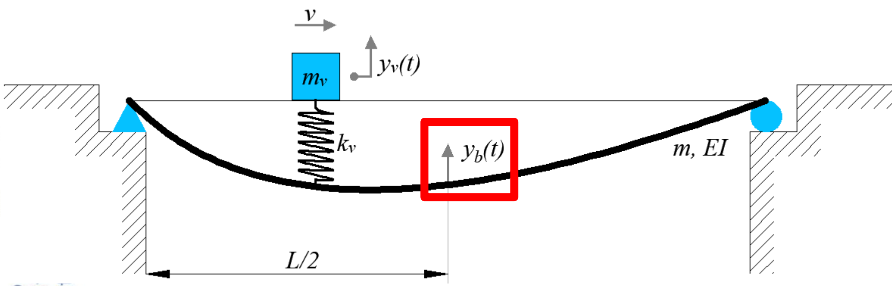
BRIDGE FIRST FREQUENCY $\omega_b = \frac{\pi^2}{L^2}\sqrt{\frac{EI}{m}}$

VEHICLE FREQUENCY $\omega_v = \sqrt{\frac{k_v}{m_v}}$

m	Beam mass per unit length
EI	Beam flexural rigidity
k_v	Vehicle stiffness
m_v	Vehicle mass
v	Vehicle constant speed

Y.-B. Yang, C. W. Lin, "**Vehicle–bridge interaction dynamics and potential applications**"
Journal of Sound and Vibration, vol.284, pp. 205–226, 2005

VBI - Equation of motions



Displacement of the bridge midspan

$$y_b = \frac{\Delta_{st}}{1-s^2}\left[\sin\left(\frac{\pi v t}{L}\right) - s\sin\left(\omega_b t\right)\right]$$

$$\Delta_{st} = -\frac{2 m_v g L^3}{\pi^4 EI}$$ STATIC DEFLECTION OF THE MIDSPAN OF THE BEAM

$$s = \frac{\pi v}{L\omega_b}$$ SPEED PARAMETER

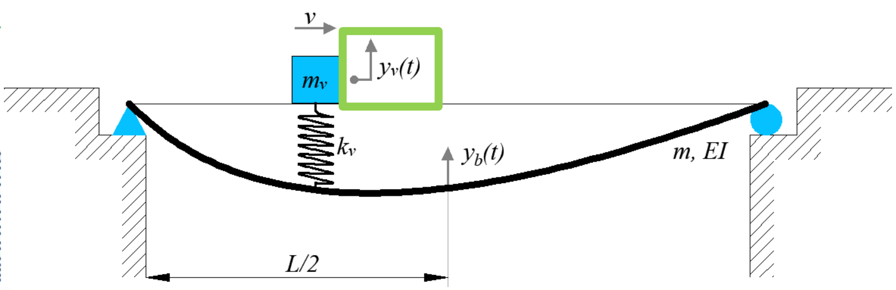
Y.-B. Yang, C. W. Lin, "Vehicle–bridge interaction dynamics and potential applications" Journal of Sound and Vibration, vol.284, pp. 205–226, 2005

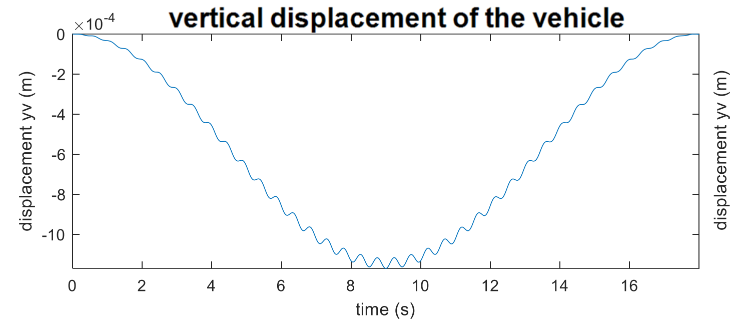
dipartimento di ingegneria unipa

Università degli Studi di Palermo

Background

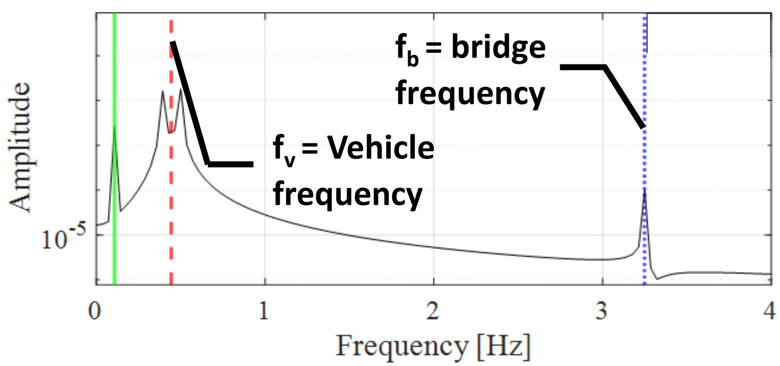
VBI - Equation of motions





Vehicle response

$$y_v = \frac{\omega_v \Delta_{st}}{2(1-s^2)}\left\{\frac{1}{\omega_v}(1-\cos(\omega_v t)) - \frac{\omega_v(\cos(2\pi vt/L)-\cos(\omega_v t))}{\omega_v^2-(2\pi vt/L)^2} - s\left[\frac{\omega_v\left(\left(\left(\pi v/L\right)-\omega_b\right)t\right)-\cos(\omega_v t)}{\omega_v^2-(\pi v/L-\omega_v)^2} - \frac{\omega_v\left(\left(\left(\pi v/L\right)+\omega_b\right)t\right)-\cos(\omega_v t)}{\omega_v^2-(\pi v/L+\omega_v)^2}\right]\right\}$$



Vehicle response spectrum

Y.-B. Yang, C. W. Lin, "Vehicle–bridge interaction dynamics and potential applications" Journal of Sound and Vibration, vol.284, pp. 205–226, 2005

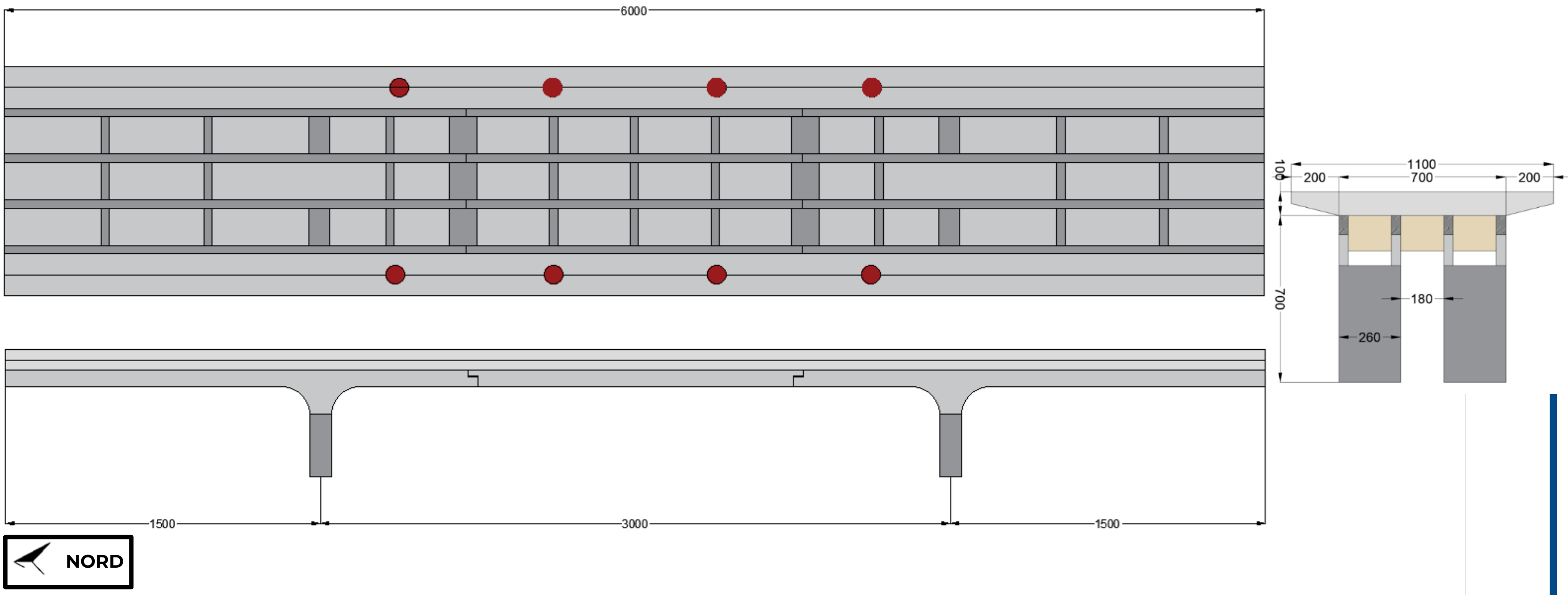
Dynamic Test OMA

Interchange 12 bridge – Dubai (UAE)

Dynamic Test OMA

Interchange 12 bridge – Dubai (UAE)

Plan, elevation and section

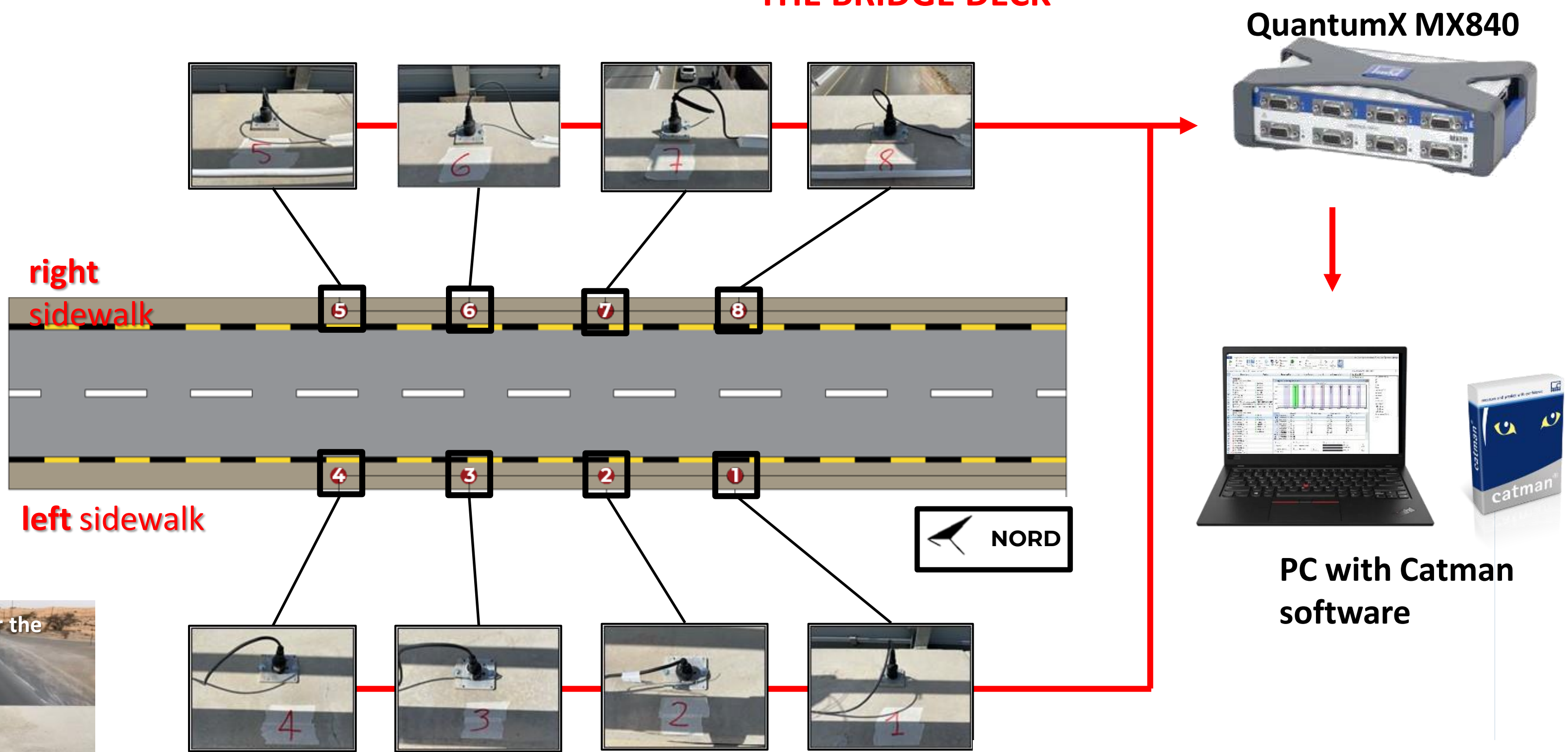


Dynamic Test OMA

Setup of the OMA test

TRADITIONAL METHOD

SENSORS positioned ON THE BRIDGE DECK

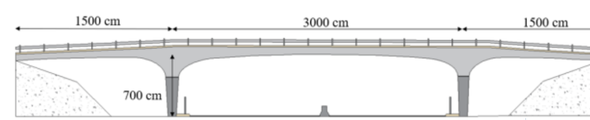


Setup:

8 piezoelectric accelerometers PCB 393A03

QuantumX MX840 module (sampling rate: 600 Hz)

PC with Catman software

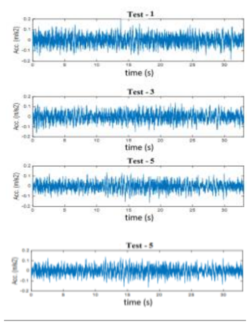


Dynamic Test OMA

OMA test: Results

TRADITIONAL METHOD

Time domain

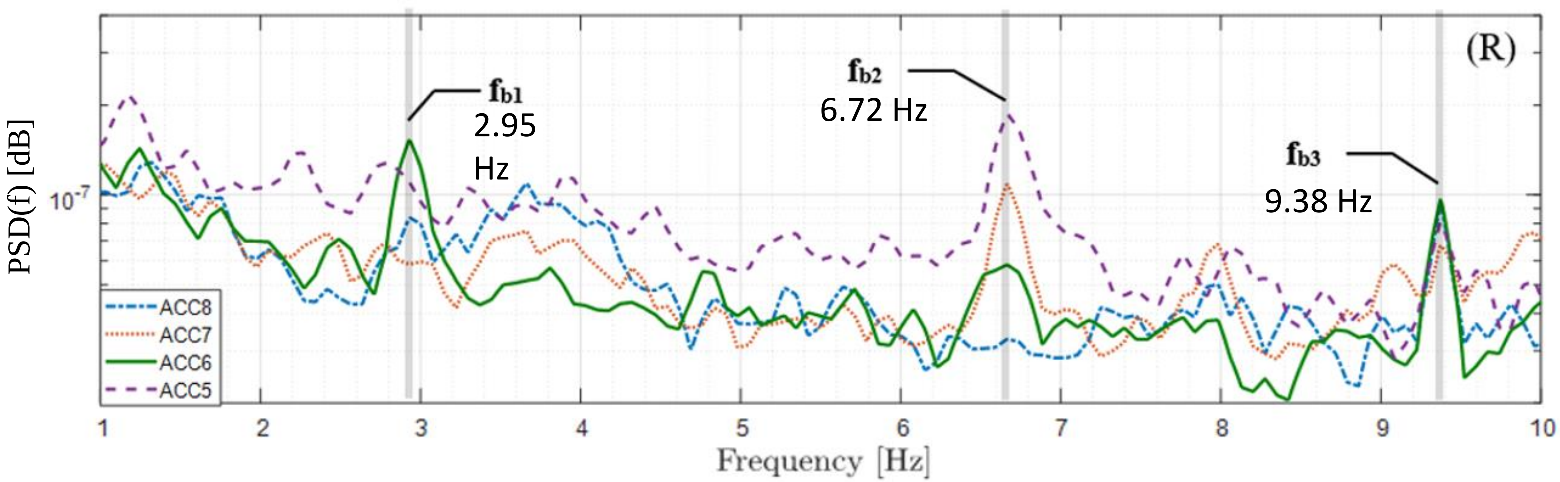


Welch's method info

Sub-signals of 10s

Overlap= 50%

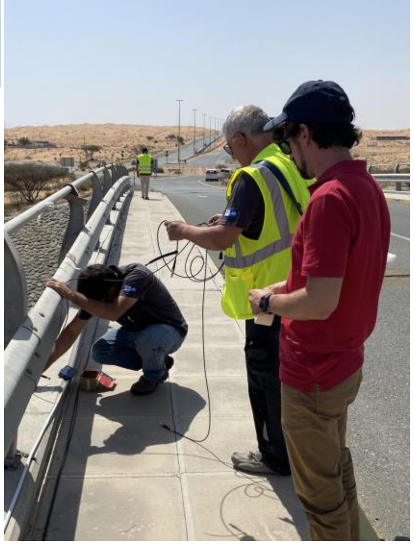
Power Spectral Density (PSD) functions of the bridge response

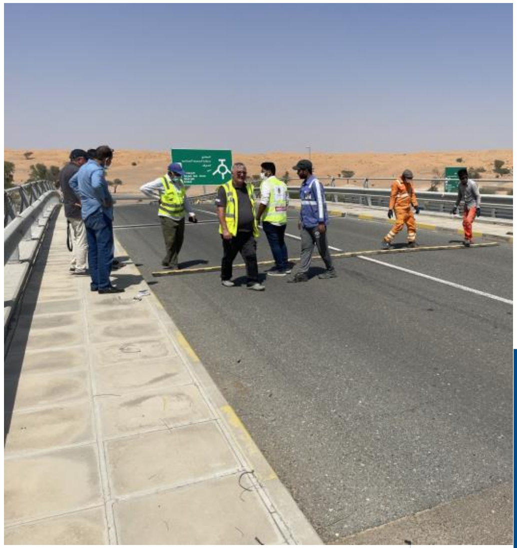


Dynamic Test OMA

TRADITIONAL METHOD

very demanding!!

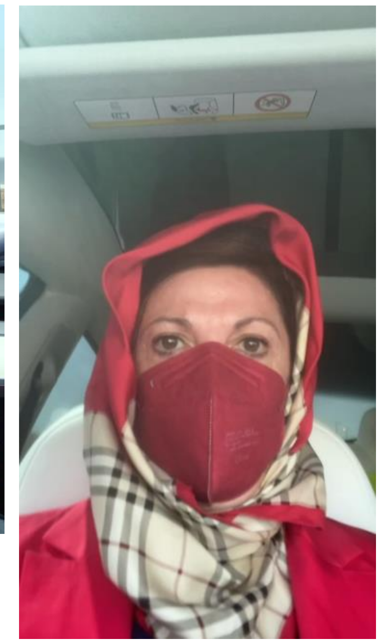




Dynamic Test OMA

VBI-based approach

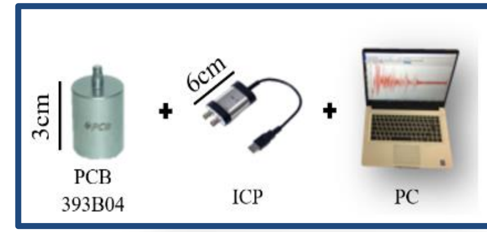
VBI-based approach EASIER!

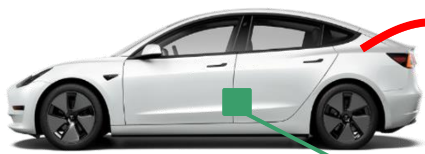


20 crossings at 5 km/h

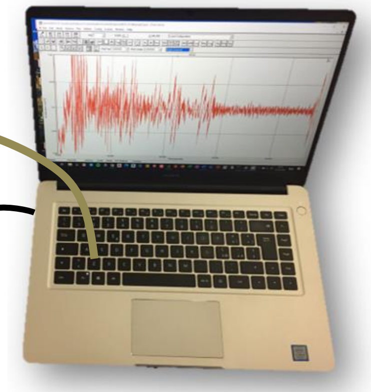
1 hour

VBI approach – setup





Electric vehicle



PC with software acquisition

Signal conditioner

Piezoelectric accelerometer PCB 393B01

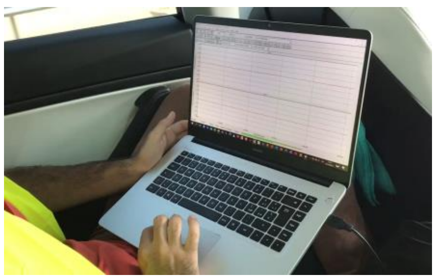
Sensitivity: 102 mV/ms2

INNOVATIVE METHOD

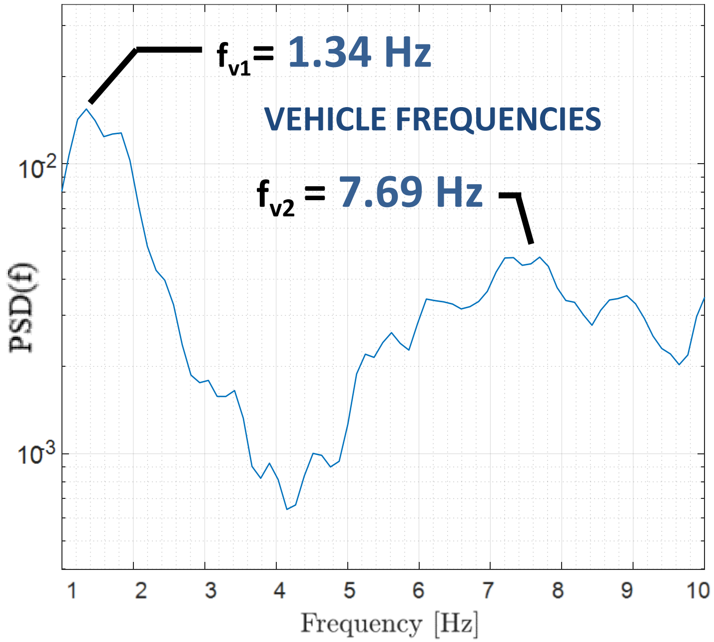
INSTRUMENTATION OF THE EXPERIMENTAL DYNAMICS LABORATORY OF THE DEPARTMENT OF ENGINEERING

VBI-based approach: Identification of the vehicle frequency

Dynamic identification of the vehicle



Power Spectral Density (PSD) functions of the vehicle response



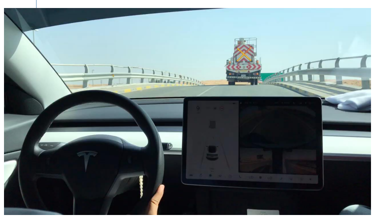
INNOVATIVE METHOD

Welch's method info

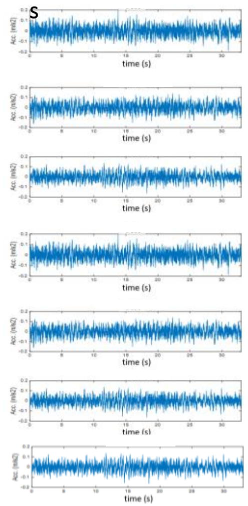
N of subsignals = 186
Overlap= 50%

Frequency Bridge

VBI-based approach: Results



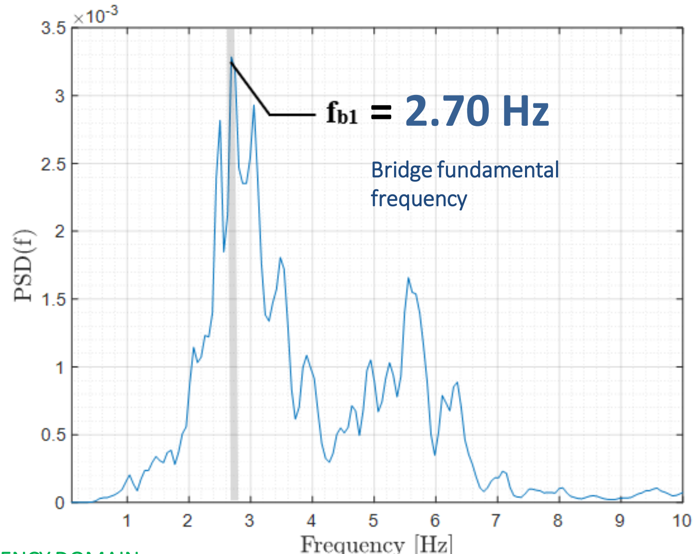
Acquisitions



TIME DOMAIN

INNOVATIVE METHOD

Power Spectral Density (PSD) functions of the vehicle vertical response



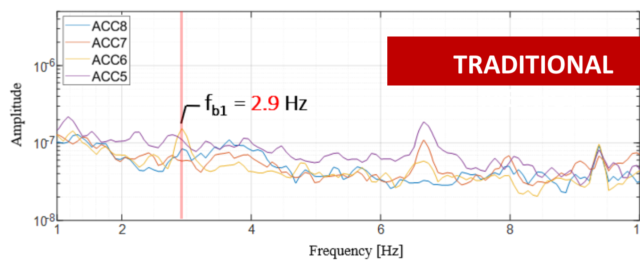
FREQUENCY DOMAIN

Welch's method info

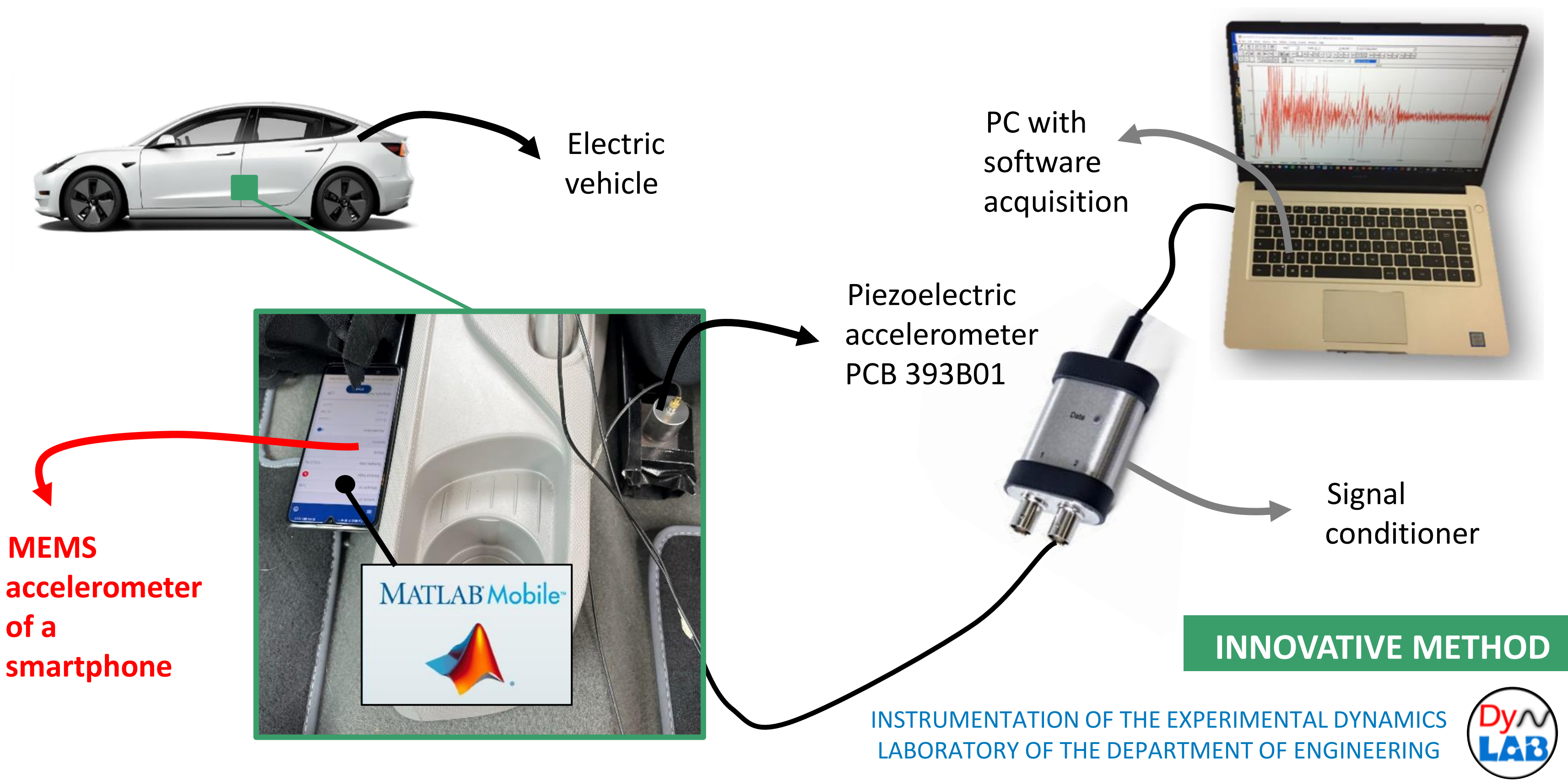
N of subsignals = 120

Overlap= 50%

TRADITIONAL



VBI approach – setup

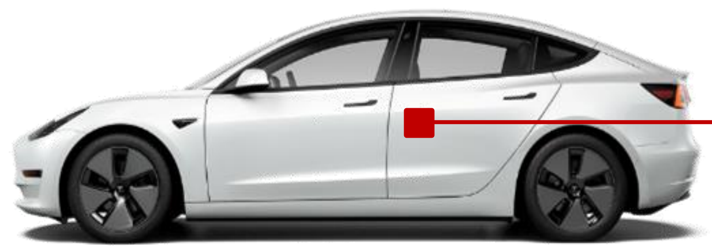


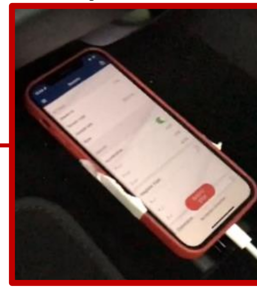
VBI-based approach: Crowdsensing integration on the setup

CROWDSENSING (almost touching the challenge!!!!!)

MEMS accelerometer of the iPhone 11

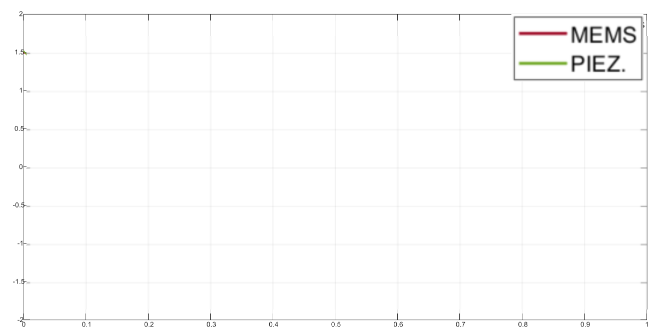
Matlab mobile app (Sampling rate 100 Hz)





Piezoelectric accelerometer

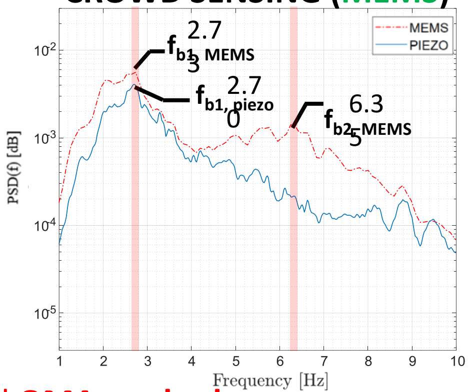
MEMS accelerometer



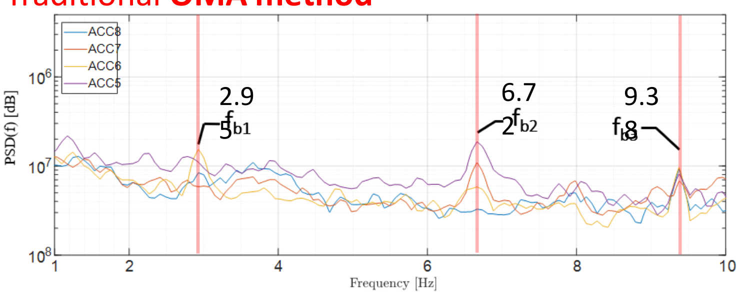
Preliminar test MEMS accelerometer

VBI-based approach: Results

VBI-based method (piezo)
vs
CROWD SENSING (MEMS)



Traditional **OMA method**



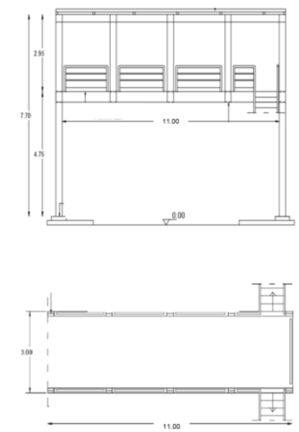
		f_{b1} [Hz]	f_{b2} [Hz]	f_{b3} [Hz]
VBI method	Piezoelectric accelerometer	2.70	-	-
	MEMS accelerometer	2.73	6.35	-
Traditional OMA method		2.95	6.72	9.38

The results of the preceding experimental tests suggest that a **VBI-based approach** used for monitoring purposes is reliable, in particular, for the identification of the **first frequency** of the bridge. It is therefore a promising procedure, which allows obtaining dynamic information of the structures without using sensors on the bridge thus greatly **reducing costs** of wide-scale infrastructural monitoring. For this reason, **further investigations** are needed to definitively make this method competitive in comparison to the traditional ones.

Moreover, monitoring through the VBI-based techniques is possible even using **low-cost and widespread accelerometers** such as those in smartphones; indeed, MEMS accelerometers allow to obtain good results comparable to the most expensive devices. This consideration is extremely important to evaluate a possible implementation of the **crowd-sensing system** on the VBI-based approach.

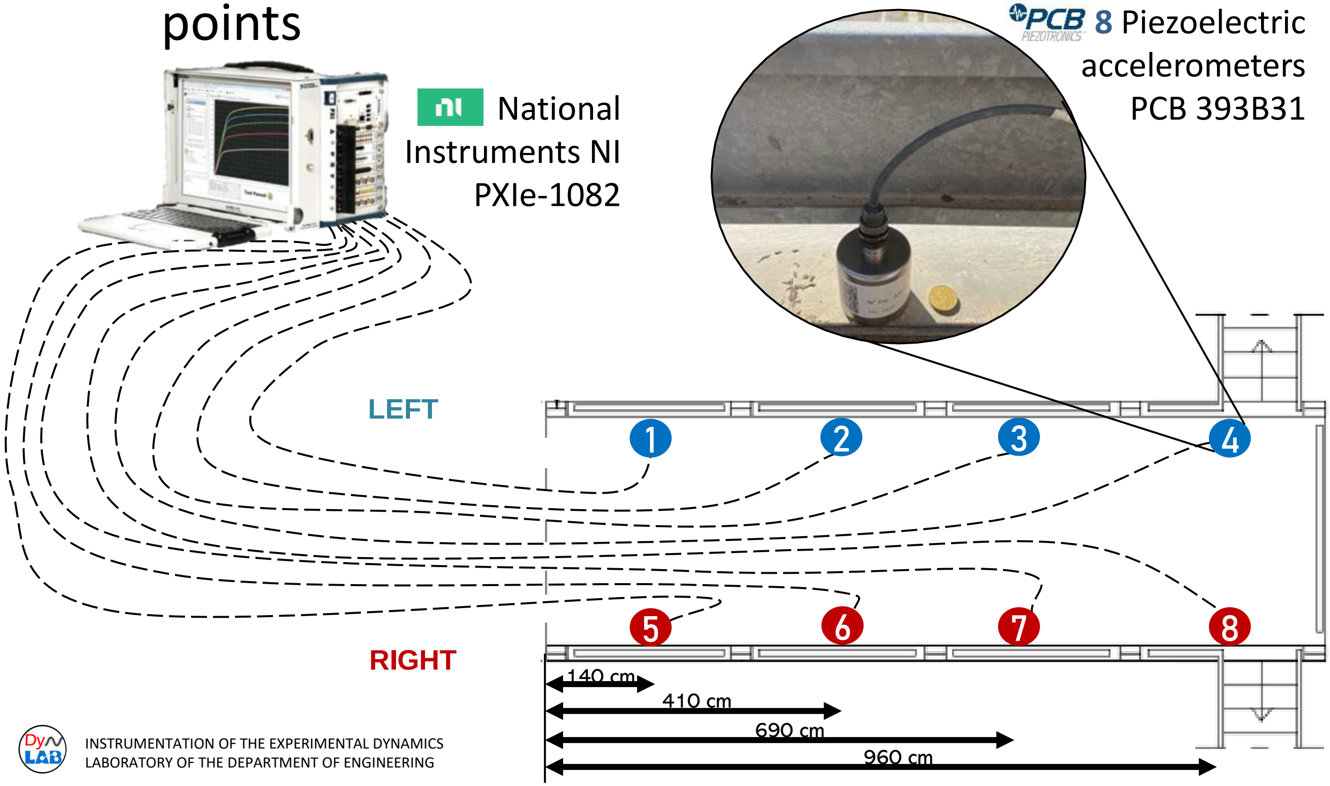
Pedestrian bridge

Palermo, Italy



TYPOLOGY	STEEL
WIDTH	3 m
LENGTH	11 m

OMA test – Measuring points



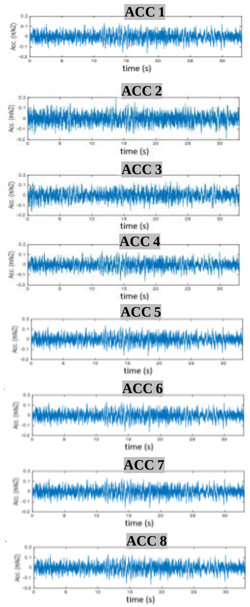
TRADITIONAL METHOD

INSTRUMENTATION OF THE EXPERIMENTAL DYNAMICS LABORATORY OF THE DEPARTMENT OF ENGINEERING

OMA test

TRADITIONAL METHOD

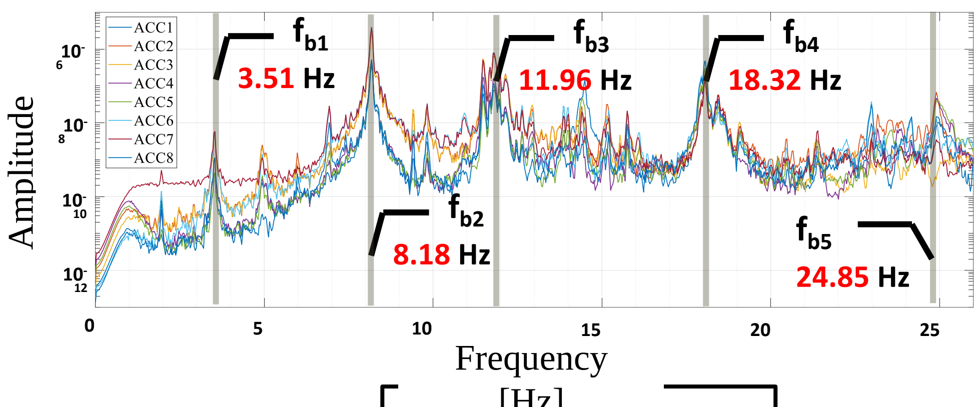
Time domain



500-second acquisitions

AMBIENT NOISE ONLY !

PSDs of the bridge response



Welch's method info

Overlap= 50%

Sampling rate = 1000 Hz

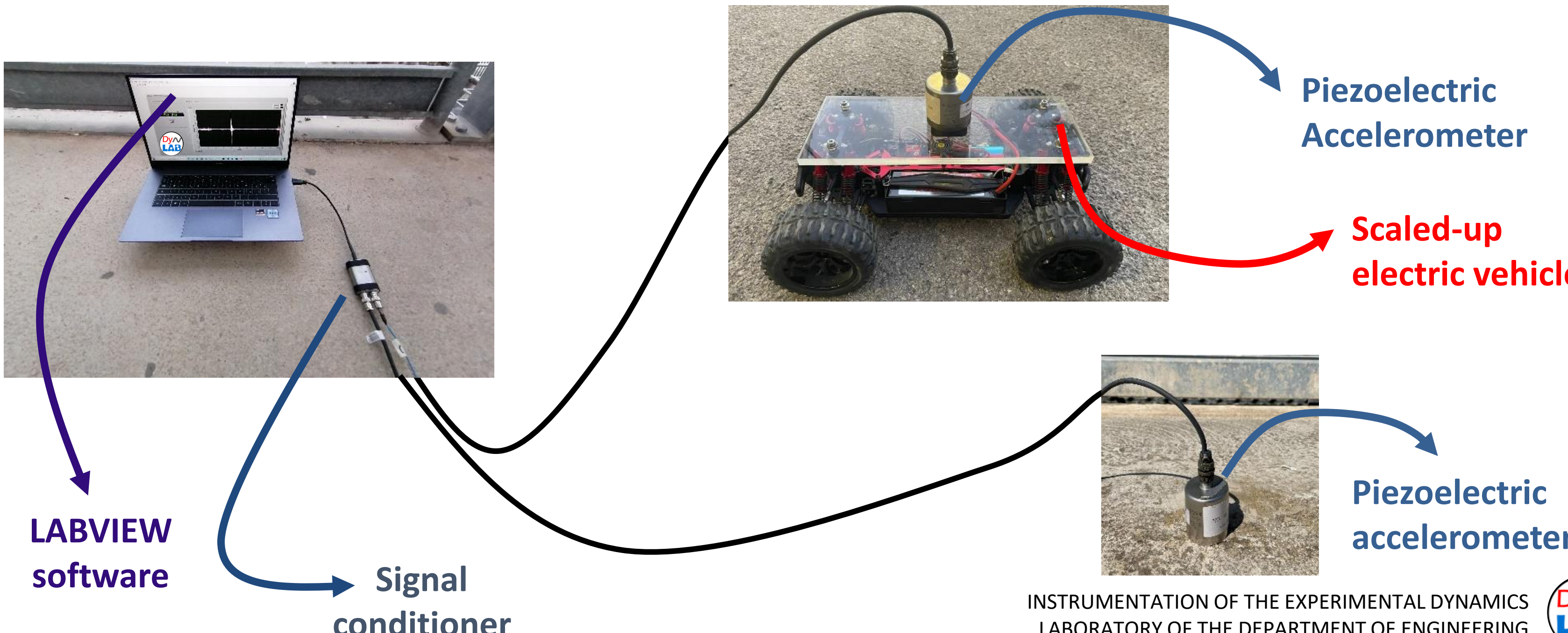
f	[Hz]
f_1	3.51
f_2	8.18
f_3	11.96
f_4	18.32
f_5	24.85

OMA test – drawback!

TRADITIONAL METHOD

VBI approach - setup

INNOVATIVE METHOD



INSTRUMENTATION OF THE EXPERIMENTAL DYNAMICS
LABORATORY OF THE DEPARTMENT OF ENGINEERING

VBI approach – mobile platform

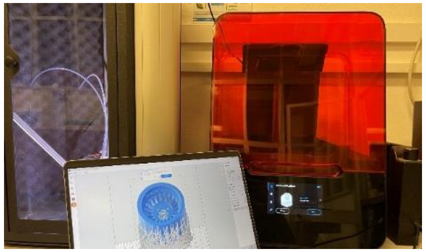
ADVANTAGES

VBI approach – mobile platform

ADVANTAGES

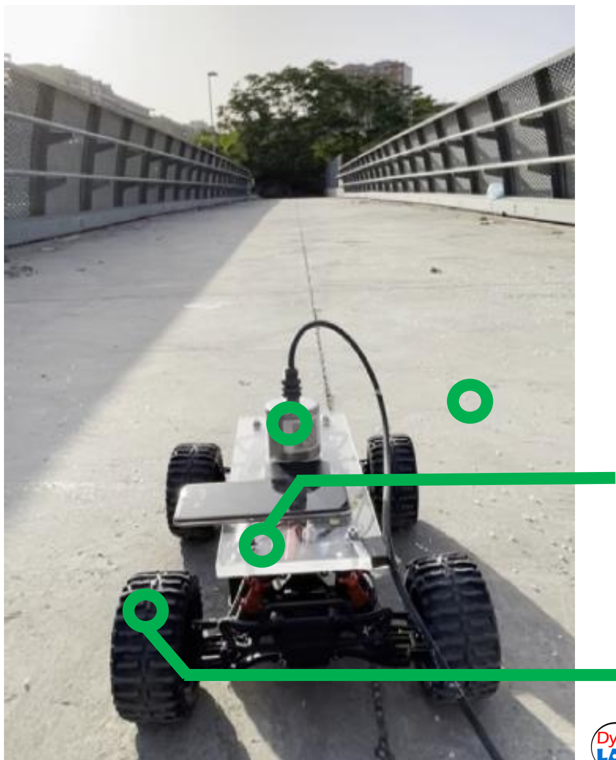
dynamic parameters adaptability

INSTRUMENTATION OF THE **EXPERIMENTAL DYNAMICS LABORATORY** OF THE DEPARTMENT OF ENGINEERING



3D PRINTING

VBI approach – mobile platform

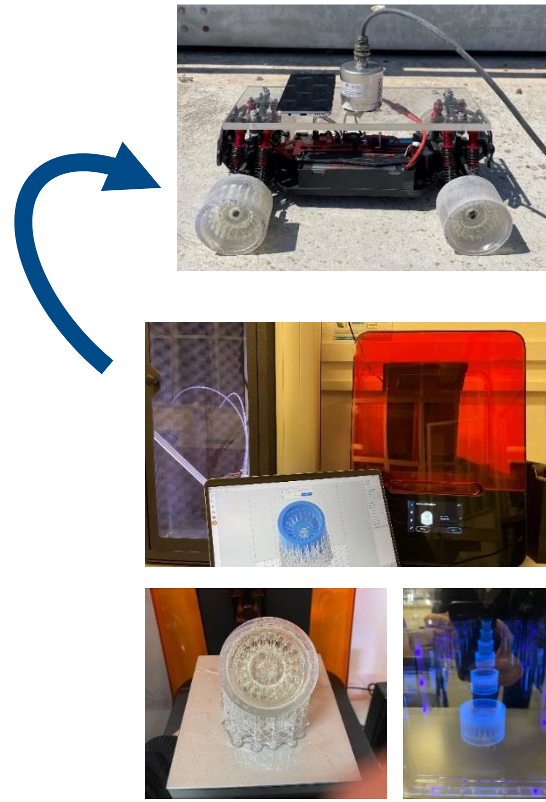


ADVANTAGES

Easily scalable
and automatable

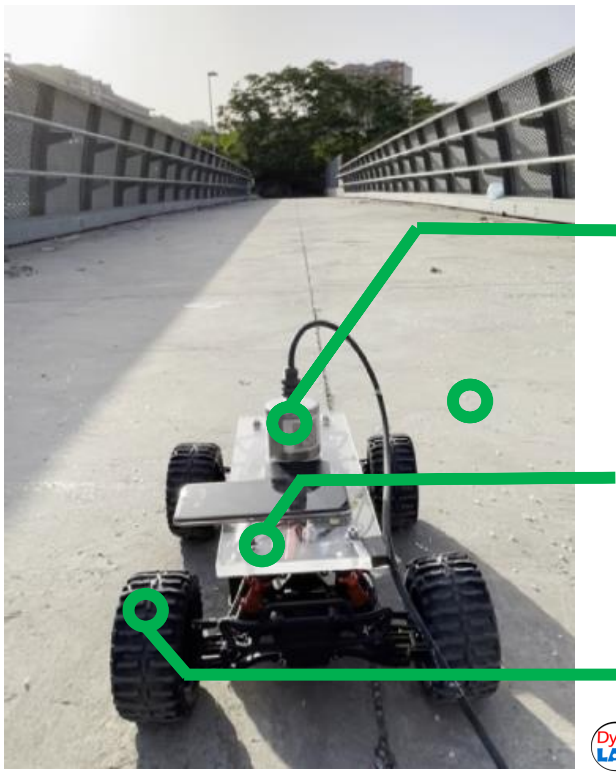
dynamic parameters adaptability

INSTRUMENTATION OF THE **EXPERIMENTAL DYNAMICS**
LABORATORY OF THE DEPARTMENT OF ENGINEERING



3D PRINTING

VBI approach – mobile platform



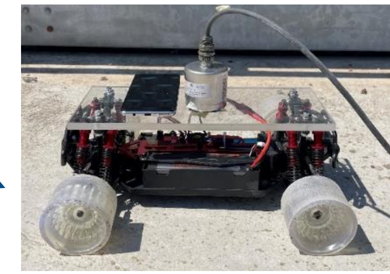
ADVANTAGES

Cost effective
multisensor platform

Easily scalable
and automatable

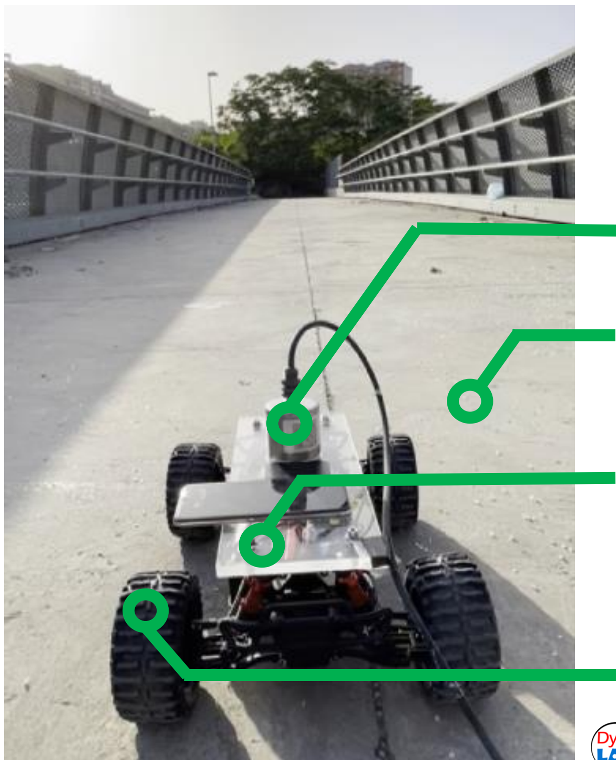
dynamic parameters adaptability

INSTRUMENTATION OF THE **EXPERIMENTAL DYNAMICS LABORATORY** OF THE DEPARTMENT OF ENGINEERING



3D PRINTING

VBI approach – mobile platform



ADVANTAGES

Cost effective
multisensor platform

Ideal for pedestrian
bridges

Easily scalable
and automatable

dynamic parameters
adaptability

INSTRUMENTATION OF THE **EXPERIMENTAL DYNAMICS**
LABORATORY OF THE DEPARTMENT OF ENGINEERING

3D PRINTING

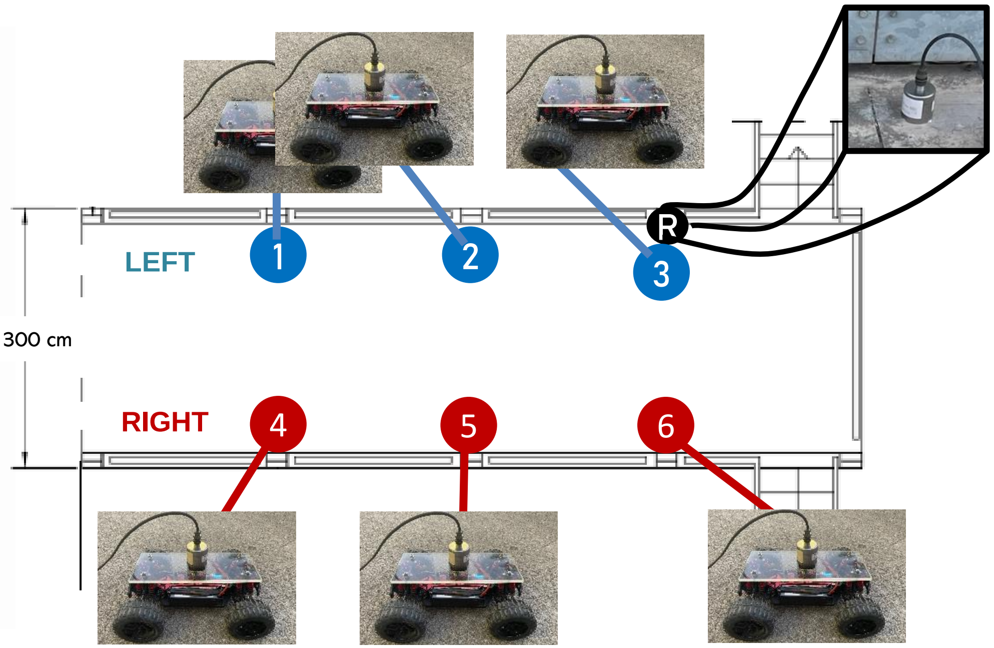
INNOVATIVE METHOD

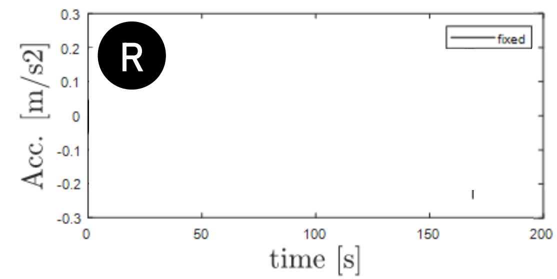
1 Record the acceleration responses

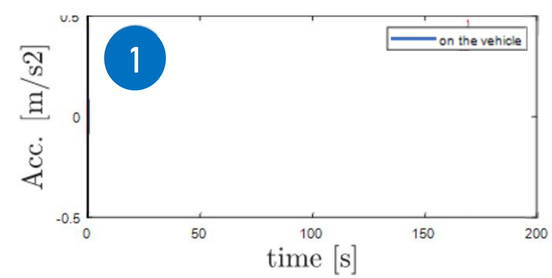
2

3

4







AMBIENT NOISE ONLY !

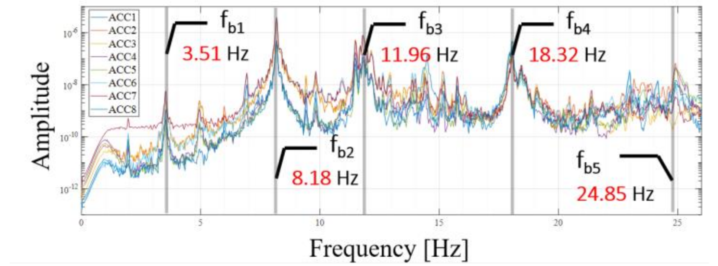
1 Record the **acceleration** responses

2 Identify the **bridge frequencies**

3

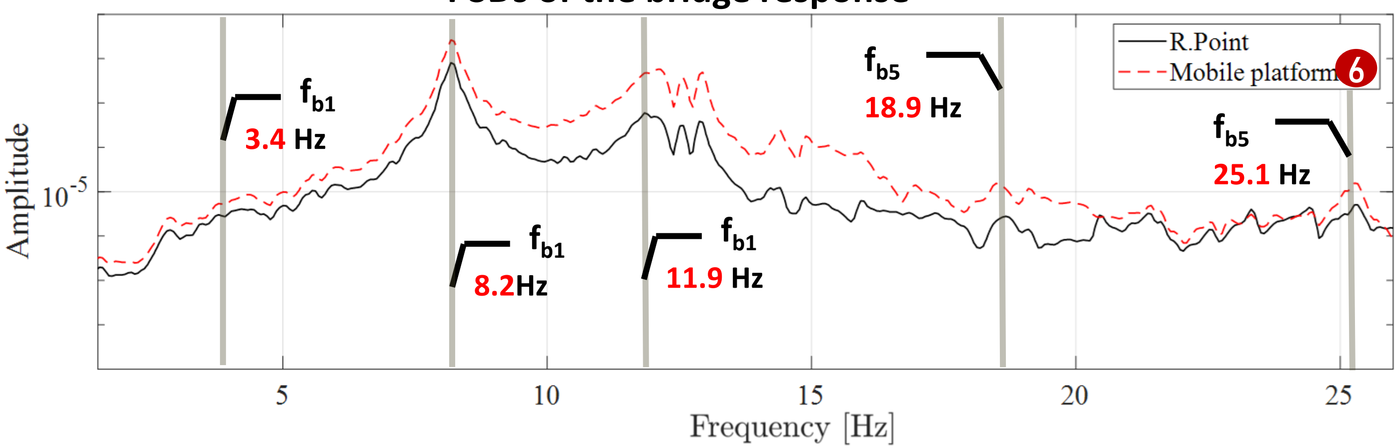
4

TRADITIONAL METHOD

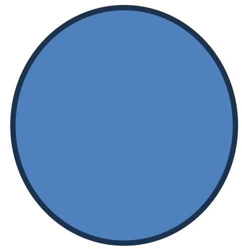


INNOVATIVE METHOD

PSDs of the bridge response



Math is still alive

$x^2 + y^2 = R^2 \Longleftrightarrow$ 

and also HT $\Rightarrow$ magnifying glass

the same when you talk about Stochastics

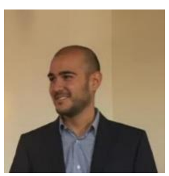
and the same about Fractional calculus !!!

$M\ddot{x}(t) + \underbrace{c\,\dot{x}(t)} + Kx(t) = F(t)$

$\hookrightarrow C_\alpha D^\alpha x(t$ $\qquad \alpha = 0, 0.1, 0.2 \ldots$ 

Let's play with Math for capturing the real physical world and give solution to us engineers in EVACES!!!

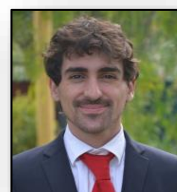
thanks ♡



Alberto Di Matteo
Researcher UNIPA

Chiara Masnata
Researcher UNIPA

Salvatore Russotto
Researcher UNIPA



Dario Fiandaca
Ph. D. Student UNIPA

P. S. F. C. next time if I did not bore you!!

METODO INNOVATIVO

Approccio VBI

10 registrazioni

20 secondi

Approccio VBI – setup

METODI INNOVATIVI

Condizionatore di segnale, ICP

MATLAB Mobile

Acceleromet… MEMS

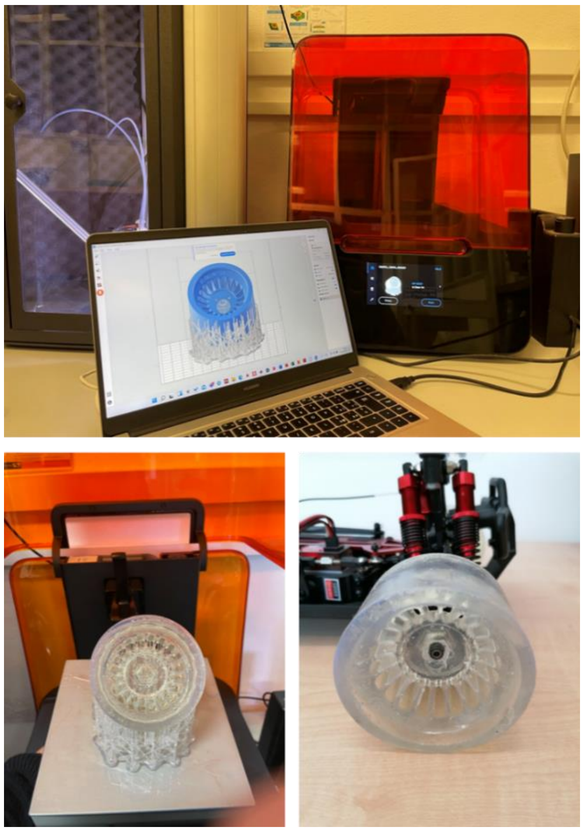
Macchina elettrica in scala 1:10

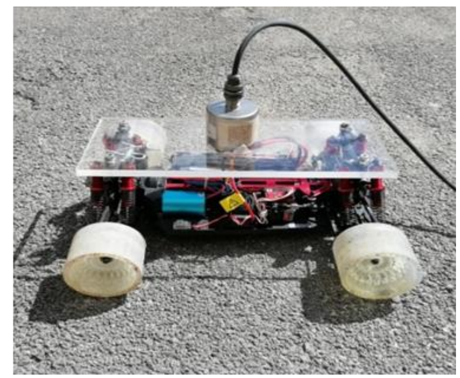
Accelerometro piezoelettrico

NATIONAL INSTRUMENTS LabVIEW Certified Developer

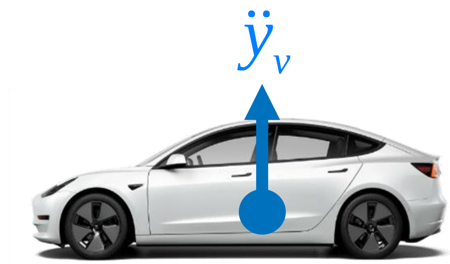
Accelerometro piezoelettrico collocato in un punto di riferimento

Strumentazione del laboratorio di dinamica sperimentale del dipartimento di ingegneria civile

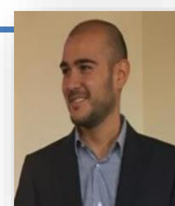


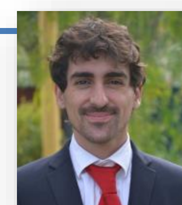


SMART MONITORING → SAFER BRIDGES



thank you





Professor
Antonina Pirrotta[1]

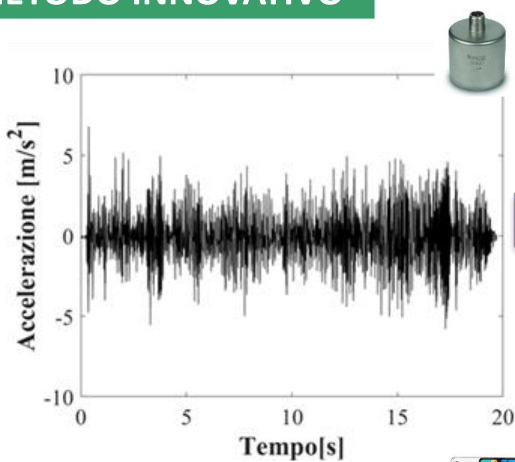
Researcher
Alberto Di Matteo[1]

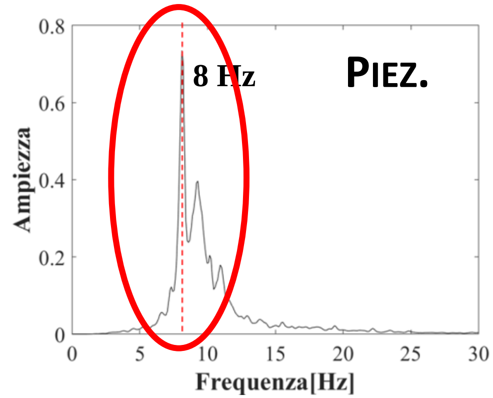
D. Fiandaca[1]
Ph. D. Student[1]

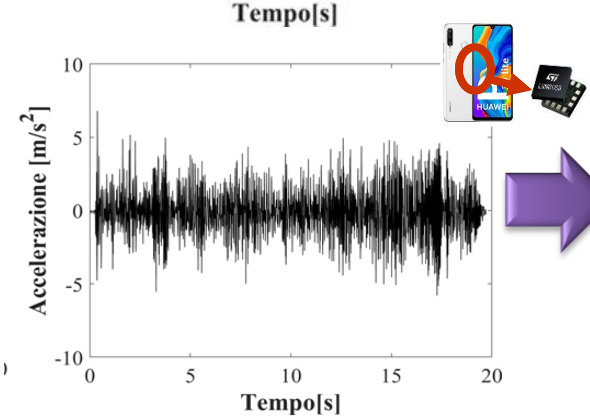
[1]Dipartimento di Ingegneria, Università degli Studi di Palermo, Italy

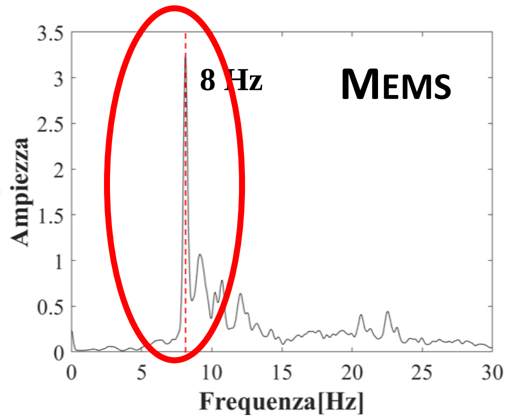
METODO INNOVATIVO

Approccio VBI





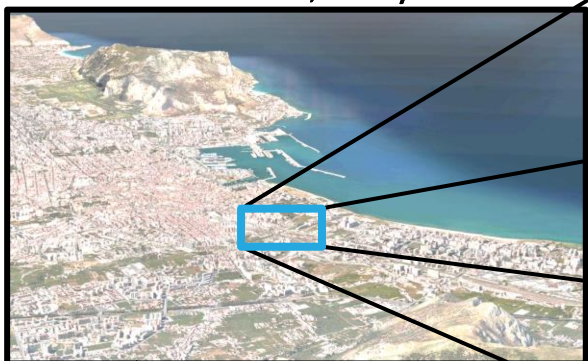




	OMA	VBI
f_{b1} [Hz]	8,09	8
f_{b2} [Hz]	18,48	/
f_{b3} [Hz]	24,9	/

Passerella pedonale adiacente al ponte delle Teste Mozze

Palermo, Italy



Lunghezza: 33 metri
Larghezza: 3,5 metri
Materiale: Acciaio

OMA test – Set-up

METODO

5 Accelerometri piezoelettrici
PCB 393B31

Scheda di acquisizione
6036E

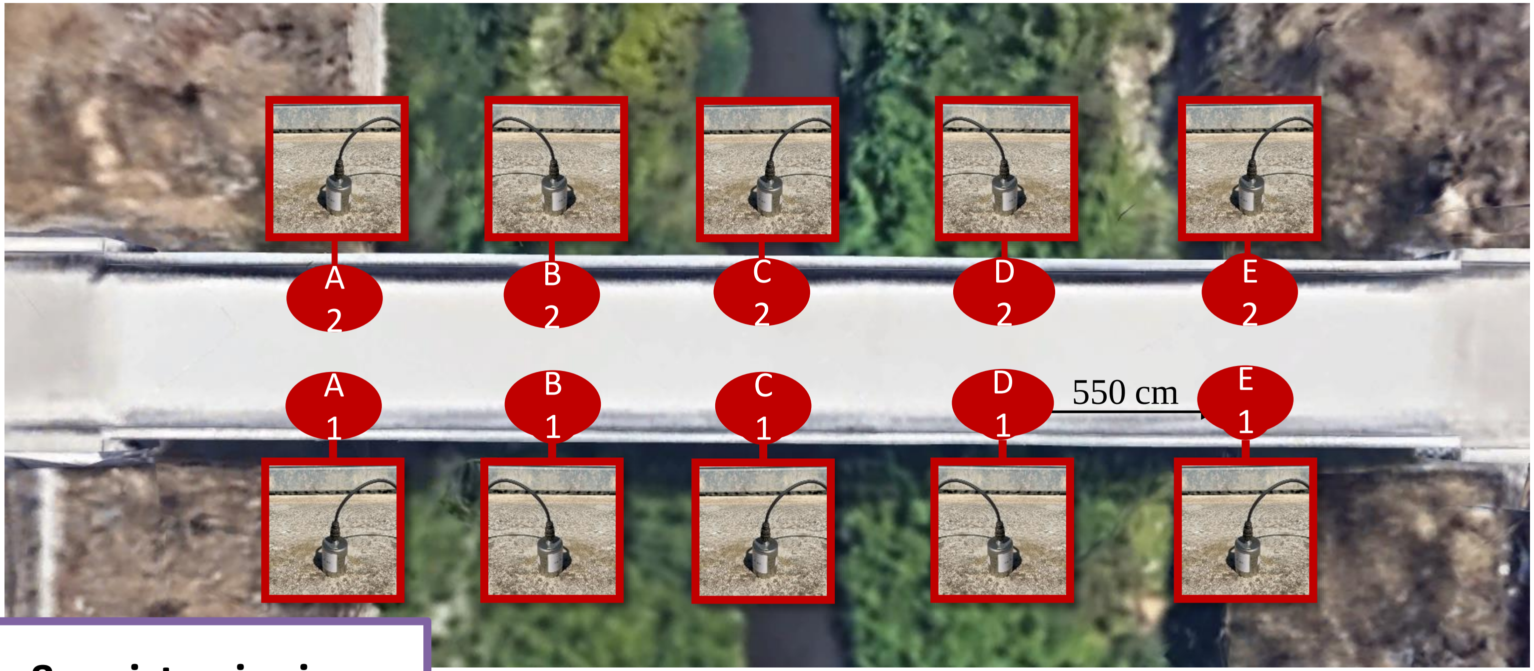
NEXUS Amplificatore di segnale

Morsettiera
NI BNC - 2110

LabVIEW Certified Developer

Strumentazione del laboratorio di dinamica sperimentale del dipartimento di ingegneria civile

Test OMA

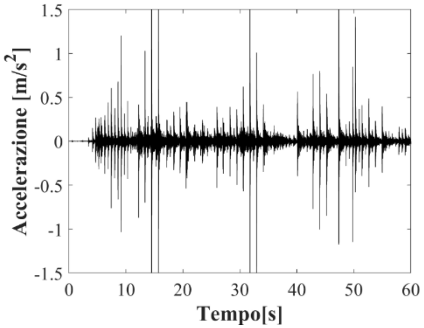


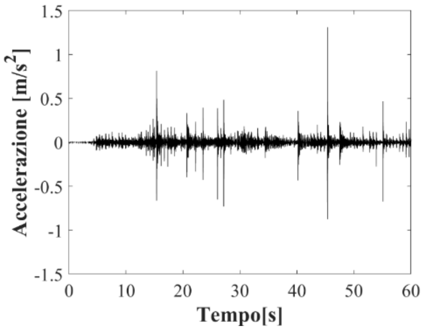
8 registrazioni

60 secondi

METODO

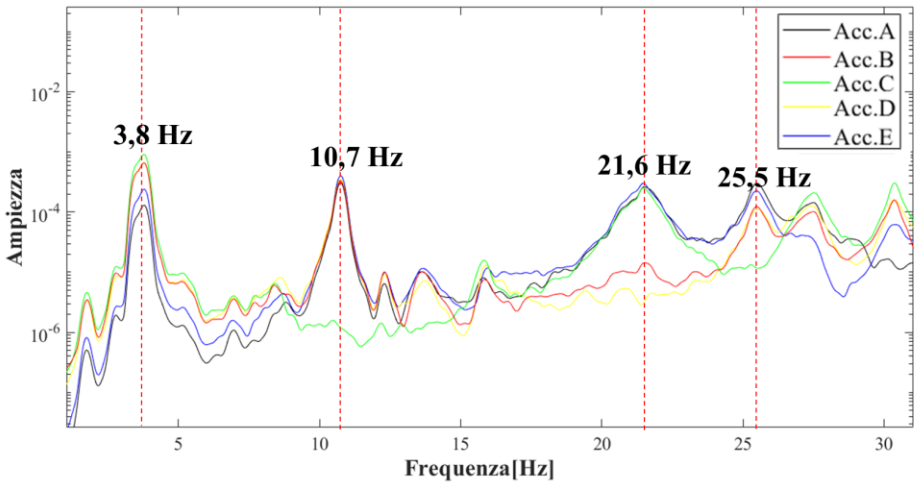
METODO





Metodo di Welch

Funzione densità spettrale di Potenza, PSD



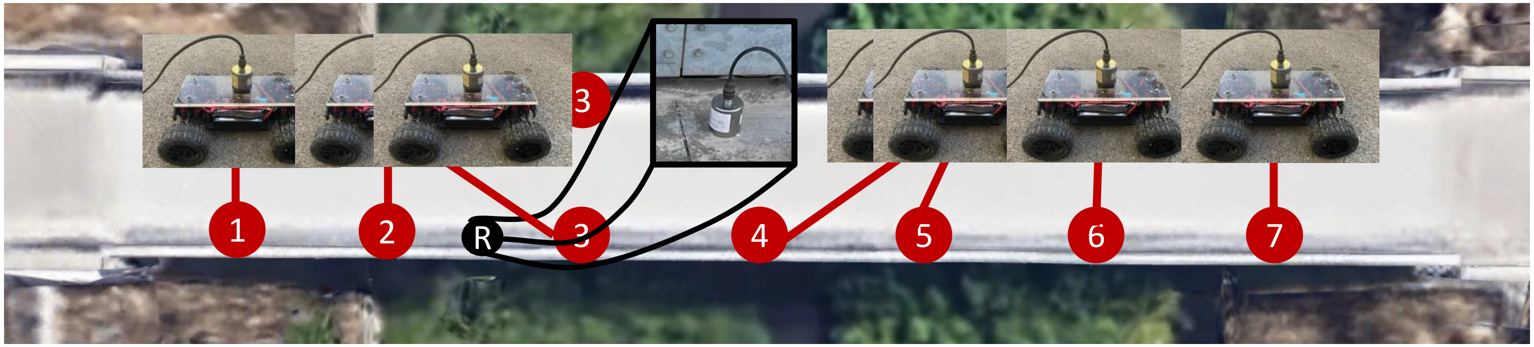
Sovrapposizione: 50%

Sotto-campioni: 10s

Frequenza di campionamento:1000 Hz

Approccio VBI

METODO INNOVATIVO

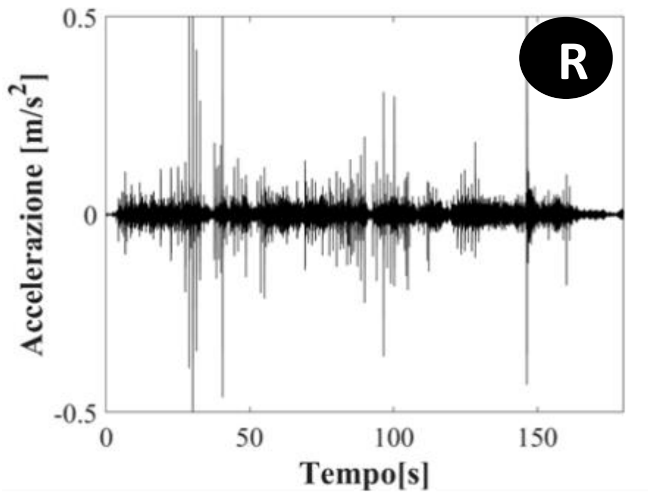


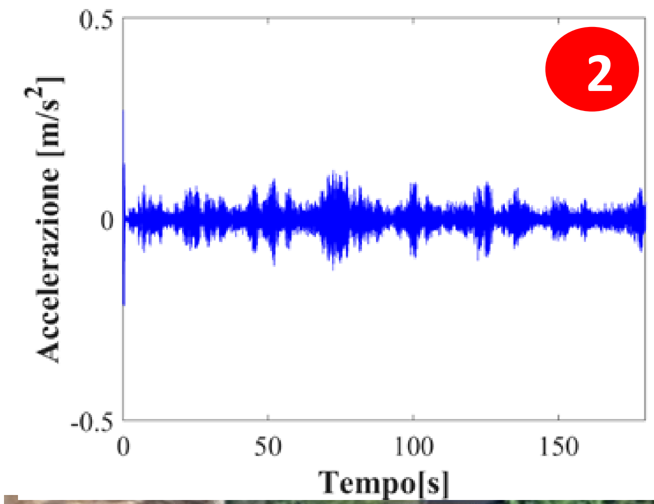
7 registrazioni

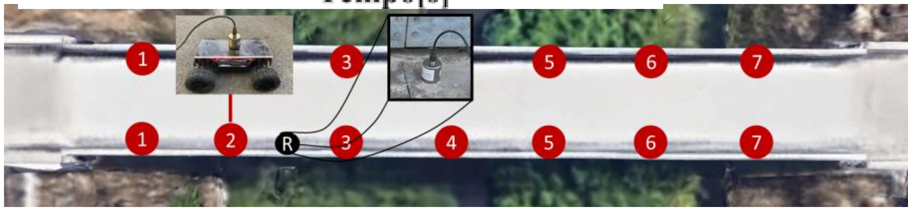
180 secondi

METODO INNOVATIVO

1 Registrazione delle accelerazioni





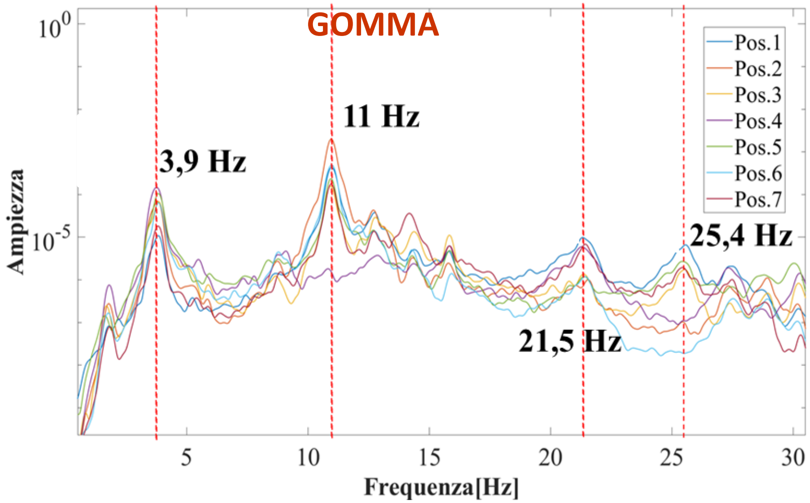


METODO INNOVATIVO

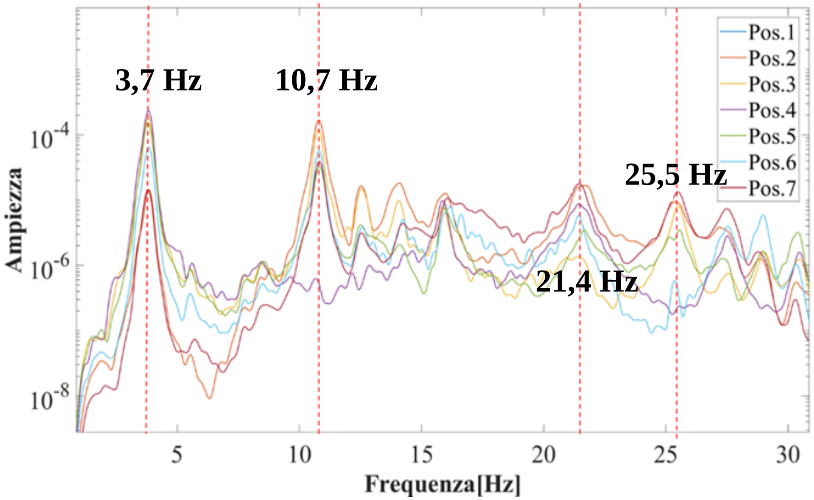
2 Identificazione delle frequenze

	OMA	VBI-GOMMA	VBI-LISCE
f_{b1} [Hz]	3,8	3,9	3,7
f_{b2} [Hz]	10,7	11	10
f_{b3} [Hz]	21,6	21,5	21,4
f_{b4} [Hz]	25,5	25,4	25,5

RUOTE IN GOMMA



RUOTE LISCE



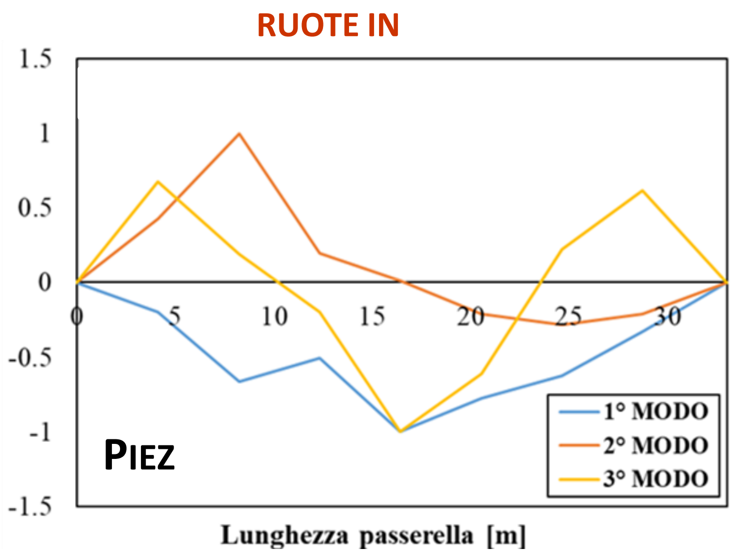
METODO INNOVATIVO

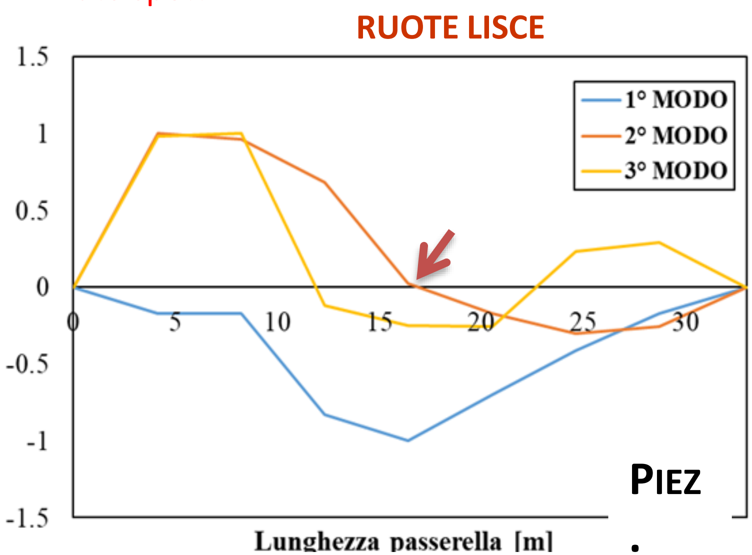
3 Calcolo delle forme modali

$$A_{ir} = \frac{S_{ir}(f_k)}{S_{rr}(f_k)}$$

Cross spettri

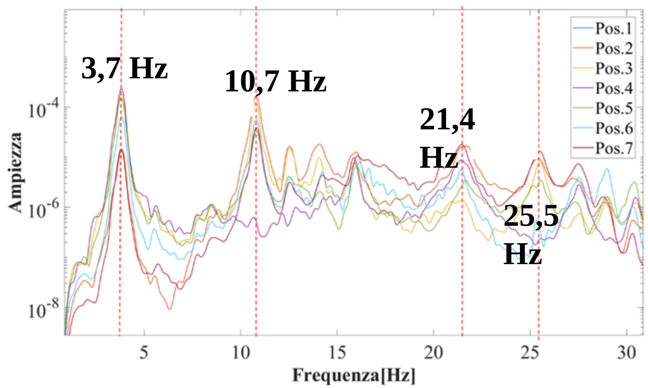
Auto spettri

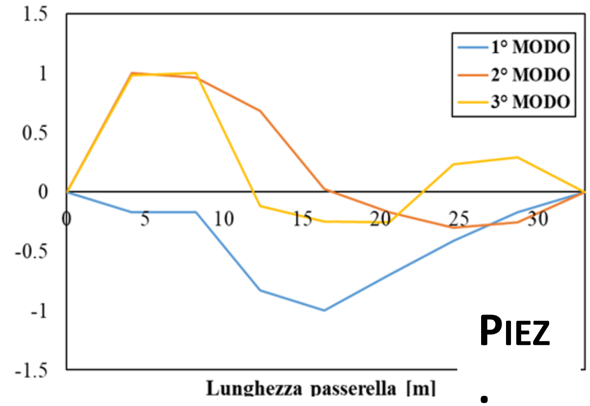




METODO INNOVATIVO

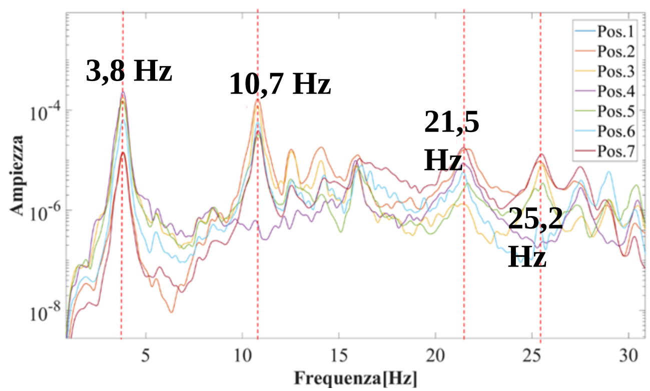
Forme modali

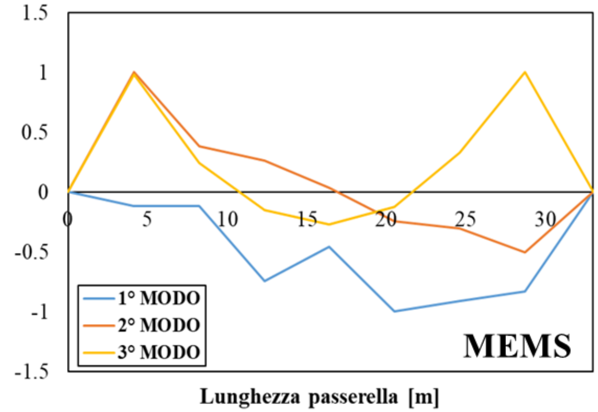




PIEZ

.





Tecniche di monitoraggio

Analisi numerica-teorica

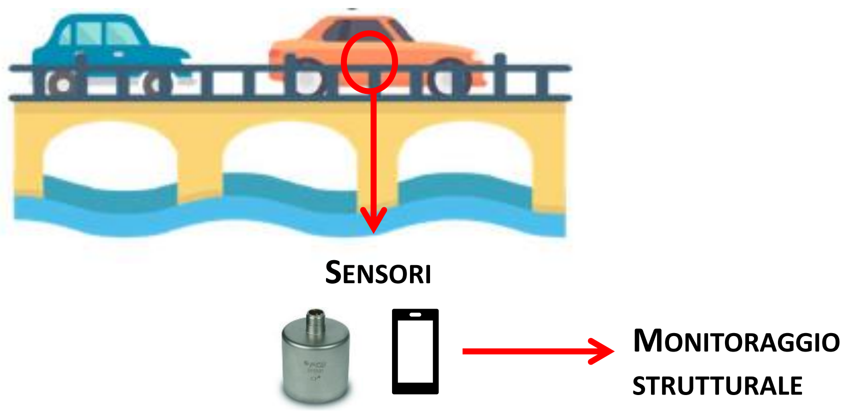
Prove sperimentali

Conclusioni

1 Buona corrispondenza del **metodo VBI** con i **metodi tradizionali**

2

3



1 Buona corrispondenza del **metodo VBI** con i **metodi tradizionali**

2 Il set- up sperimentale **vantaggioso**

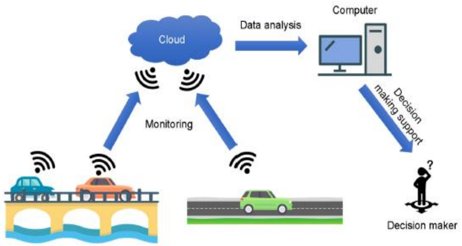
Condizionatore di segnale, ICP

3

1 Buona corrispondenza del **metodo VBI** con i **metodi tradizionali**

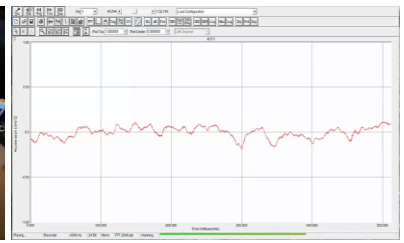
2 Il set- up sperimentale **economico**

3 **Accelerometri MEMS**



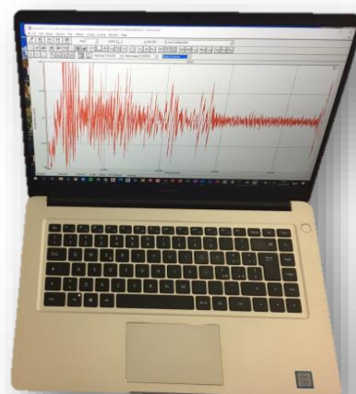
Experimental campaign: SET-UP

PIEZOELECTRIC ACCELEROMETER



PIEZOELECTRIC ACCELEROMETER
PCB - 393B31

PCB - ICP



dipartimento di ingegneria unipa

Dynamic Test OMA

VBI-based approach: SETUP

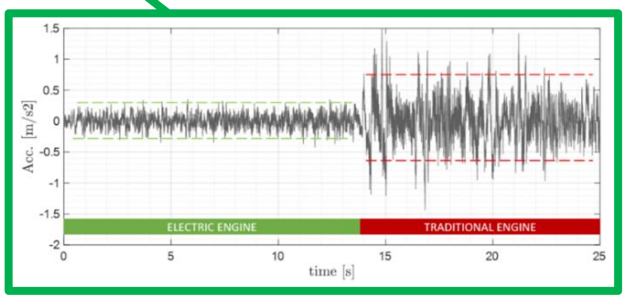
Setup:

1 electric vehicle

1 piezoelectric accelerometer PCB 393B04

ICP - USB Signal Conditioner 485B39

PC with Spectraplus (sampling rate 4000 Hz)



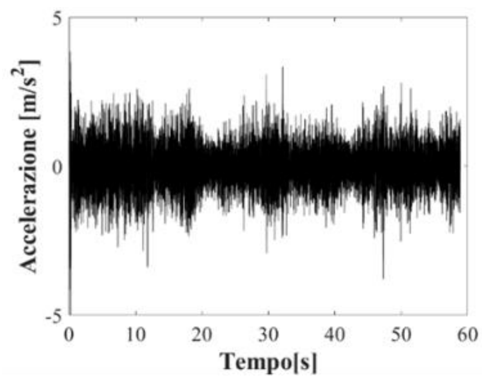
ADVANTAGES OF ELECTRIC ENGINE

INNOVATIVE METHOD

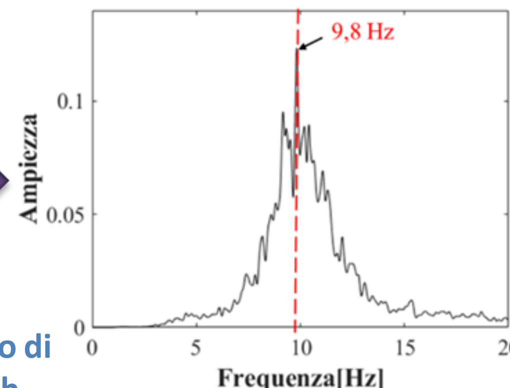
Grazie per l’attenzione

Identificazione veicolo

Tracciato rettilineo
Velocità costante
6 Passaggi
60 secondi



Metodo di Welch



Funzione densità spettrale di Potenza, PSD

Sovrapposizione: 50%

Sotto-campioni: 10s

Frequenza di campionamento:1000 Hz